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THE MISSISSIPPIAN LEADVILLE LIMESTONE EXPLORATION PLAY, UTAH AND COLORADO – EXPLORATION TECHNIQUES AND STUDIES FOR INDEPENDENTS

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THE MISSISSIPPIAN LEADVILLE LIMESTONE EXPLORATION PLAY, UTAH AND COLORADO – EXPLORATION TECHNIQUES AND STUDIES FOR INDEPENDENTS

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ABSTRACT

The Mississippian Leadville Limestone is a shallow, open-marine, carbonate-shelf deposit. The Leadville has produced over 53 million barrels (8.4 million m^3) of oil/condensate from seven fields in the Paradox fold and fault belt of the Paradox Basin, Utah and Colorado. The environmentally sensitive, 7500-square-mile (19,400 km^2) area that makes up the fold and fault belt is relatively unexplored. Only independent producers operate and continue to hunt for Leadville oil targets in the region. The overall goal of this study is to assist these independents by (1) developing and demonstrating techniques and exploration methods never tried on the Leadville, (2) targeting areas for exploration, and (3) conducting a detailed reservoir characterization study. The final results will hopefully reduce exploration costs and risks, especially in environmentally sensitive areas, and add new oil discoveries and reserves.

This report covers research and technology transfer activities for the first half of the fourth project year (October 1, 2006, through March 31, 2007), Budget Period II. Research consisted of chemical analyses of the samples and interpretations of the results from a surface geochemical survey over the Lisbon and Lightning Draw Southeast fields, Utah.

Lisbon field is ideal for a surface geochemical survey because proven hydrocarbons underlie the area, it is easily accessible, and the surface geology is similar to the structure of the field. Proving the success of relatively low-cost geochemical surveys at Lisbon field will allow independent operators to reduce risks and minimize impacts on environmentally sensitive areas while exploring for Leadville targets. To the southwest, Leadville gas and condensate were recently discovered at Lightning Draw Southeast field, which has similar geology to Lisbon field. However, the field is still near original reservoir pressure and therefore hydrocarbon microseepage to the surface may be more significant than at Lisbon field.

The geochemical survey consisted of collecting shallow soil samples over and around the fields covering the gas cap, oil leg (present only at Lisbon), and background "barren" areas to map the spatial distribution of potential surface hydrocarbon anomalies. In addition, samples were collected near oil, gas, and dry wells for analogue matching purposes and to refine the discriminant model for the fields. Approximately 400 samples, collected along sampling grids and around selected wells, were analyzed for 40 hydrocarbon compounds in the C_1 to C_{12} range, 53 major and trace elements, seven anion species, and synchronous scanned fluorescence.

The main conclusion drawn from this evaluation of surface geochemical methods over the Lisbon and Lightning Draw Southeast fields is that certain low-cost ($100 to $200 per sample), non-invasive geochemical methods are effective as pre-screening and follow-up tools in the exploration for Leadville hydrocarbon reservoirs. Hydrocarbon microseepage over the gas cap, oil leg, and water leg at Lisbon field is distinguished based on a linear combination of thermally desorbed hydrocarbons in surface soil samples, and outcrop fracture-fill soil and lichen samples. Both light and heavy aromatic hydrocarbon anomalies are evident in surface soils over the case-study fields. Fluorescence spectral patterns in anomalous areas are indicative of a weathered light oil or condensate. Narrow normal- and iso-alkane anomalies in the C_2 to C_6 range are evident in 6-foot-deep (2-m) free-gas samples over Lightning Draw Southeast field.

Recommendations for future surface geochemical surveys for Leadville Limestone exploration in the Paradox Basin are: (1) reconnaissance exploration should include the collection of surface soils (outcrop fracture-fill lichen and soils where applicable) for hydrocarbon and major/trace element analyses, and (2) anomalous areas identified in

reconnaissance soil surveys should be followed up with the extraction and hydrocarbon analysis of deep free-gas samples collected at short horizontal intervals (<300 feet [<100 m]). The short-interval free-gas method is also recommended for testing existing seismic anomalies for hydrocarbon and carbon dioxide anomalies.

Technology transfer activities during this quarter consisted of technical and non-technical presentations, and a publication. An abstract describing the surface geochemical survey and results was submitted to the American Association of Petroleum Geologists for presentation at the October 2007 Rocky Mountain Section meeting in Snowbird, Utah. The project home page was updated on the Utah Geological Survey Web site.

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EXECUTIVE SUMMARY

The Mississippian Leadville Limestone is a shallow, open-marine, carbonate-shelf deposit. The Leadville has produced over 53 million barrels (8.4 million m^3) of oil/condensate from seven fields in the Paradox fold and fault belt of the Paradox Basin, Utah and Colorado. These fields are currently operated by independent producers. The environmentally sensitive, 7500-square-mile (19,400 km^2) area that makes up the fold and fault belt is relatively unexplored. Only independent operators continue to hunt for Leadville oil targets in the region. The overall goal of this study is to assist these independents by (1) developing and demonstrating techniques and exploration methods never tried on the Leadville Limestone, (2) targeting areas for exploration, and (3) conducting a detailed reservoir characterization study. The final results will hopefully reduce exploration costs and risk especially in environmentally sensitive areas, and add new oil discoveries and reserves.

To achieve this goal and carry out the Leadville Limestone study, the Utah Geological Survey (UGS), Eby Petrography & Consulting, Inc., and Direct Geochemical have entered into a cooperative agreement with the U.S. Department of Energy (DOE), National Petroleum Technology Office, Tulsa, Oklahoma. The research is funded as part of the DOE Advanced and Key Oilfield Technologies for Independents (Area 2 – Exploration) Program. This report covers research and technology transfer activities for the first half of the fourth project year (October 1, 2006, through March 31, 2007), Budget Period II. Research consisted of chemical analyses of the samples and interpretations of the results from a surface geochemical survey over the Lisbon and Lightning Draw Southeast fields, Utah.

Surface geochemical surveys have helped identify areas of poorly drained or by-passed oil in other basins. Lisbon field is ideal for a surface geochemical survey because proven hydrocarbons underlie the area, sample sites are relatively easily accessible, and the surface geology is similar to the structure of the field. Lisbon field is the largest Leadville producer and is still actively producing oil and gas. The surface geology at Lisbon field consists of a major anticline along a large normal fault. Proving the success of relatively low-cost geochemical surveys at Lisbon field will allow independent operators to reduce risks and minimize impacts on environmentally sensitive areas while exploring for Leadville targets.

The geochemical survey consisted of collecting about 200 shallow soil samples at 1500-foot intervals (500 m) on a 16-square-mile (42 km^2) rectangular grid over and around the Lisbon field to map the spatial distribution of surface hydrocarbon anomalies. The sampling grid extends beyond the proven limits of Lisbon field to establish background readings. The area chosen sufficiently covers the oil leg, gas cap, and water leg/background barren areas. In addition, 90 samples were collected near gas, oil, and dry wells for analogue matching purposes and to refine the discriminant model for Lisbon field. To the southwest, the recently discovered Lightning Draw Southeast field has similar geology to Lisbon field, both in terms of structure and a Leadville reservoir. It consists of two producing wells, primarily gas and condensate, along with barren dry wells off structure. However, the field is still near original reservoir pressure and therefore hydrocarbon microseepage to the surface may be more significant than at Lisbon field. The surface geochemical survey was expanded to include this new field and the surrounding area, with about 80 samples collected along northwest-southeast and northeast-southwest grid lines and 45 samples around both the producing wells and barren dry wells. Free-gas samples (40) were collected over Lightning Draw Southeast field and known non-productive areas off the structure. Finally, joints in the Jurassic Navajo and Entrada Sandstones

were also investigated as pathways for hydrocarbon microseepage to the surface. Sandstone outcrops have parallel and polygonal joints filled with soil, sand, bryophytes, and lichen. Over 60 samples were collected along joints for geochemical analyses.

Geochemical analyses were conducted for 40 hydrocarbon compounds in the C_1 to C_{12} range, 53 major and trace elements, seven anion species, and for synchronous scanned fluorescence analyses. The main conclusion drawn from this evaluation of surface geochemical methods over the Lisbon and Lightning Draw Southeast fields is that certain low cost ($100 to $200 per sample), non-invasive geochemical methods are effective as pre-screening and follow-up tools in the exploration for Leadville hydrocarbon reservoirs.

Hydrocarbon microseepage over the gas cap, oil leg, and water leg at Lisbon field is distinguished based on a linear combination of thermally desorbed hydrocarbons in surface soil samples, and outcrop fracture-fill soil and lichen samples. Important variables for distinguishing productive and barren areas are alkanes and aromatics in the C_1 to C_6 range. The compositional character of microseepage in surface soils is more distinct over the Lisbon gas cap relative to the water leg than is the oil leg. Both the outcrop lichen and soil samples better discriminate between the Lisbon gas cap, oil leg, and water leg in comparison with the surface soils. Outcrop fracture-fill media would therefore be the preferred sample media in areas of abundant outcrop. Productive “Lisbon-type” microseepage signatures are observed over Lightning Draw Southeast field southwest of Lisbon field. Compositional signatures over Lightning Draw Southeast also predict productive parts of Lisbon.

Hydrocarbon concentrations in the C_1 to C_{12} range are also anomalous over parts of Lisbon and Lightning Draw Southeast fields. The anomalies probably represent microseepage that ascended faults in the Lisbon and Lightning Draw Southeast anticlines because of the close spatial association of the anomalies with documented faults, particularly in the case of Lisbon. It is unlikely that the hydrocarbon anomalies reflect surface contamination from exploration and production activities because most anomalies occur upwind of production, and some anomalies are situated in areas with no current or historic production.

Both light and heavy aromatic hydrocarbon anomalies are evident in surface soils over Lisbon and Lightning Draw Southeast fields. Fluorescence spectral patterns in anomalous areas are indicative of a weathered light oil or condensate. The dust from asphalt roads contained in soil samples is a potential contaminant that creates false anomalies in the heavy aromatic spectrum (that is, 395 to 470 nm SSF intensities). Contaminated samples near roads were therefore removed from the database prior to interpretation. Heavy aromatic hydrocarbon anomalies are spatially correlated with crosscutting faults at Lisbon, and a 2400-foot-long (800-m) anomaly occurs upwind of an active gas condensate well without nearby paved roads. The anomalies therefore likely reflect condensate seeps along faults cutting the Lisbon and Lightning Draw Southeast anticlines. Narrow (that is, 450 to 900 feet [150-300 m]) normal- and iso-alkane anomalies in the C_2 to C_6 range are evident in 6-foot-deep (2-m) free-gas samples over Lightning Draw Southeast field. Carbon dioxide and hydrogen are also anomalous in free gas along the trend of the field.

A unique cadmium-uranium-molybdenum-vanadium-manganese-lead assemblage in surface soils is spatially associated with parts of the Lisbon and Lightning Draw Southeast fields. In the case of Lisbon field this element assemblage presumably reflects mechanical and chemical dispersion from the exposed Triassic Chinle Formation. At Lightning Draw Southeast field, however, there is no exposed Chinle, and thus the anomalies probably reflect chemical dispersion of these elements from an underlying source. In both cases, heavy hydrocarbons are present in the surface media to act as a reductant for deposition of these elements. A larger number of major/trace elements are anomalous, over productive versus non-productive areas, in outcrop lichen than in outcrop fracture soils. This observation possibly reflects the ability of the lichen to hold (chelate) metals obtained by uptake from ground water. The lichen would therefore be a better sample medium in areas of abundant outcrop in terms of high-contrast, trace-metal anomalies.

Recommendations for future surface geochemical surveys for Leadville Limestone exploration in the Paradox Basin are (1) reconnaissance exploration should include the collection of surface soils (outcrop fracture-fill lichen and soils where applicable) for hydrocarbon and major/trace element analyses, and (2) anomalous areas identified in reconnaissance soil surveys should be followed up with the extraction and hydrocarbon analysis of deep free-gas samples collected at short horizontal intervals (<300 feet [<100 m]). The short-interval free-gas method is also recommended for testing existing seismic anomalies for hydrocarbon and carbon dioxide anomalies.

Technology transfer activities for the reporting period consisted of technical and non-technical presentations, and a publication. An abstract describing the surface geochemical survey and results was submitted to the American Association of Petroleum Geologists for presentation at the October 2007 Rocky Mountain Section meeting in Snowbird, Utah. The presentations, made at a Petroleum Technology Transfer Council workshop, a gathering of exploration geologists from various companies in Houston, Texas, and the Utah Association of Professional Landmen monthly meeting, summarized the project objectives and results thus far. Project team members published a Semi-Annual Technical Progress Report detailing project work, results, and recommendations. The project home page was updated on the Utah Geological Survey Web site.

INTRODUCTION

Project Overview

The Mississippian Leadville Limestone has produced over 53 million barrels (bbls) (8.4 million m^3) of oil/condensate from seven fields in the northern Paradox Basin region, referred to as the Paradox fold and fault belt, of Utah and Colorado (figure 1). All of these fields are currently operated by independent producers. There have been no significant new oil discoveries since the early 1960s, and only independent producers continue to explore for Leadville oil targets in the region, 85 percent of which is under the stewardship of the federal government. This environmentally sensitive, 7500-square-mile (19,400 km^2) area is relatively unexplored with only about 100 exploratory wells that penetrated the Leadville (less than one well per township), and thus the potential for new discoveries remains great.

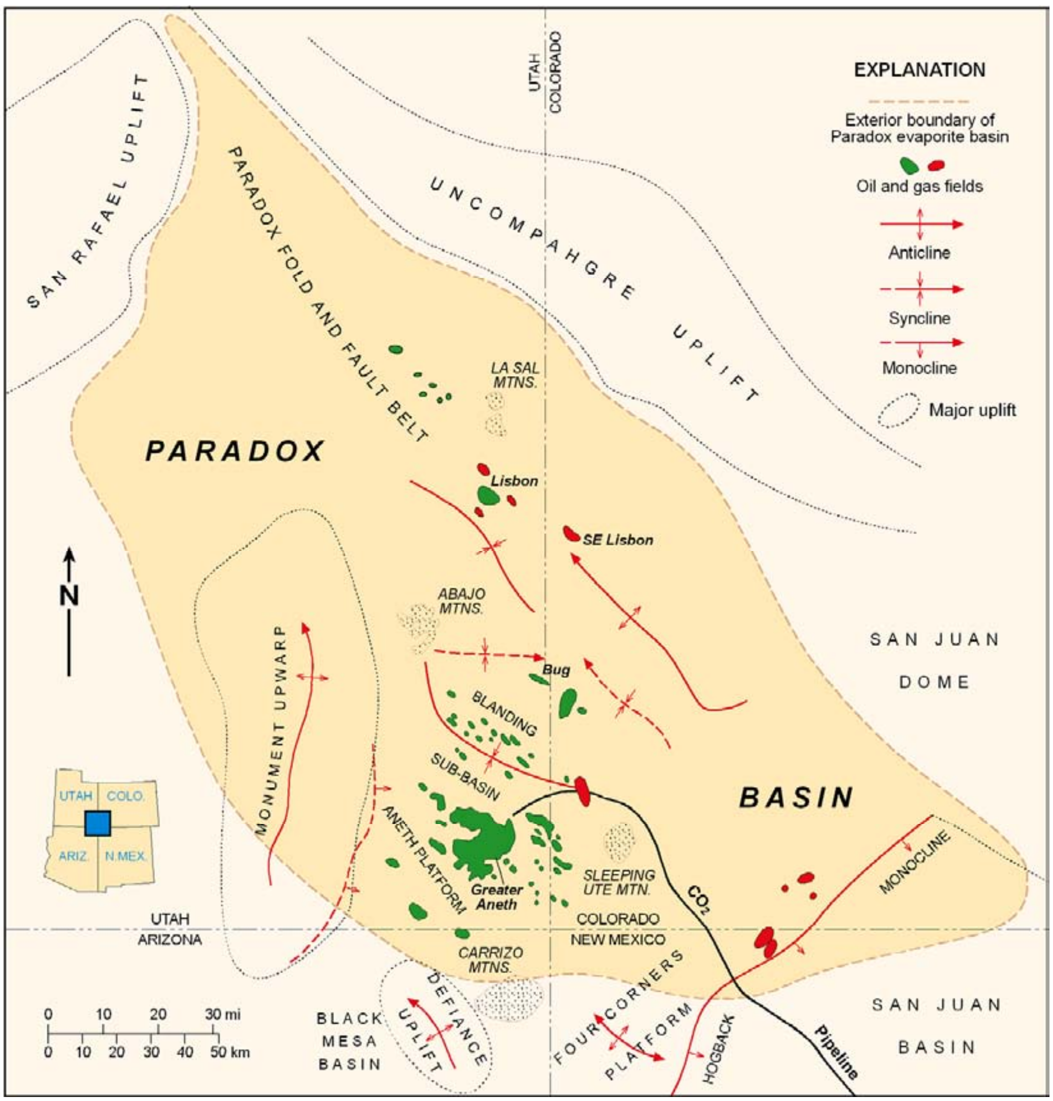


Figure 1. Oil and gas fields in the Paradox Basin of Utah, Colorado, Arizona, and New Mexico (modified from Harr, 1996).

The overall goals of this study are to (1) develop and demonstrate techniques and exploration methods never tried on the Leadville Limestone, (2) target areas for exploration, (3) increase deliverability from new and old Leadville fields through detailed reservoir characterization, (4) reduce exploration costs and risk especially in environmentally sensitive areas, and (5) add new oil discoveries and reserves.

The Utah Geological Survey (UGS), Eby Petrography & Consulting, Inc., and Direct Geochemical have entered into a cooperative agreement with the U.S. Department of Energy (DOE) as part of its Advanced and Key Oilfield Technologies for Independents (Area 2 – Exploration) Program. The project is being conducted in two phases, each with specific objectives and separated by a continue-stop decision point based on results as of the end of Phase I (Budget Period I). The objective of Phase I was to conduct a case study of the Leadville reservoir at Lisbon field (the largest Leadville oil producer in the Paradox Basin), San Juan County, Utah, in order to understand the reservoir characteristics and facies that can be applied regionally. Phase I has been completed and Phase II (Budget Period II) approved by DOE. The first objective of Phase II is to conduct a low-cost field demonstration of new exploration technologies to identify potential Leadville oil migration directions (evaluating the middle Paleozoic hydrodynamic pressure regime) and surface geochemical anomalies, especially in environmentally sensitive areas. The second objective is to determine regional facies (evaluating cores, geophysical well logs, outcrop, and modern analogs), identify potential oil-prone areas based on shows (using low-cost epifluorescence techniques), and target areas for Leadville exploration.

These objectives are designed to assist the independent producers and explorers who have limited financial and personnel resources. All project maps, studies, and results are, or will be, publicly available in digital (interactive, menu-driven products on compact disc) or hard-copy format and presented to the petroleum industry through a proven technology transfer plan. The technology transfer plan includes a Technical Advisory Board composed of industry representatives operating in the Paradox Basin and a Stake Holders Board composed of representatives of state and federal government agencies, and groups with a financial interest within the study area. Project results are, or will be disseminated via the UGS Web site, technical workshops and seminars, field trips, technical presentations at national and regional professional meetings, convention displays, papers in various technical or trade journals, and UGS publications.

This report covers research and technology transfer activities for the first half of the fourth project year (October 1, 2006, through March 31, 2007), Budget Period II. Research consisted of chemical analysis of the samples and interpretations of the results from a surface geochemical survey over Lisbon (the project case-study field in Phase I) and Lightning Draw Southeast fields, Utah (figure 2).

Project Benefits and Potential Application

Exploring the Leadville Limestone is high risk, with less than a 10 percent chance of success based on the drilling history of the region. Prospect definition often requires expensive, three-dimensional (3D) seismic acquisition, at times in environmentally sensitive areas. These facts make exploring difficult for independents that have limited funds available to try new, unproven techniques that might increase the chance of successfully discovering oil. We believe that one or more of the project activities will reduce the risk taken by an independent producer

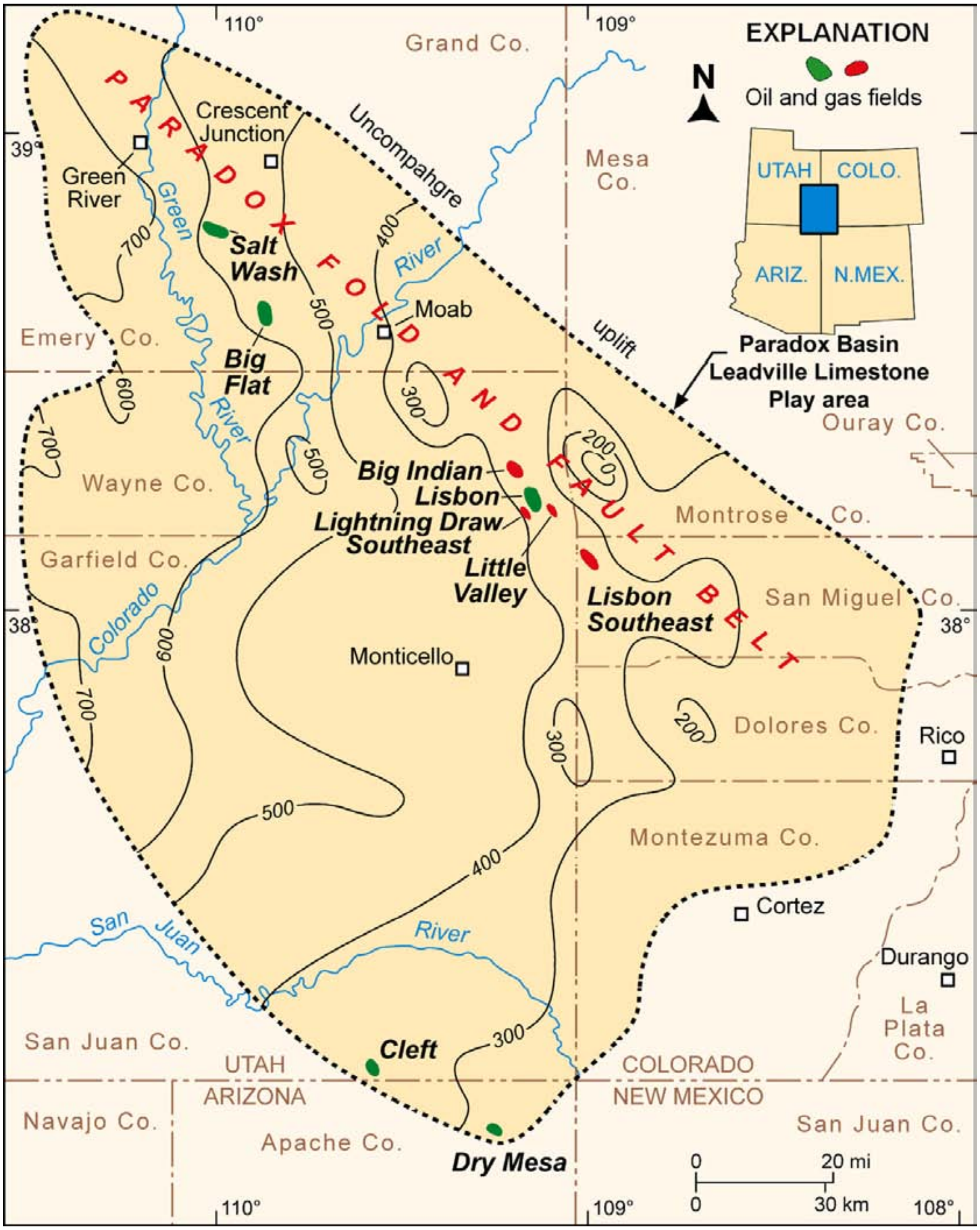


Figure 2. Location of fields that produce from the Mississippian Leadville Limestone, Utah and Colorado. Thickness of the Leadville is shown; contour interval is 100 feet (modified from Parker and Roberts, 1963).

in looking for Leadville oil, not only in exploring but in using a new technique. For example, the independent would not likely attempt surface geochemical surveys without first knowing they have been proven successful in the region. Our project proves geochemical surveys are an effective technique in environmentally sensitive areas, thus saving independents both time and money exploring for Leadville oil.

Another problem in exploring for oil in the Leadville Limestone is the lack of published or publicly available geologic and reservoir information, such as regional facies maps, complete reservoir characterization studies, surface geochemical surveys, regional hydrodynamic pressure regime maps, and oil show data and migration interpretations. This project provides this information to save independents cash and manpower resources which they simply do not possess or normally have available only for drilling. The technology, maps, and studies generated from this project will help independents to identify or eliminate areas and exploration targets prior to spending significant financial resources on seismic data acquisition and potential environmental litigation, and therefore increase the chance of successfully finding new economic accumulations of Leadville oil.

These benefits may also apply to other high-risk, sparsely drilled basins or regions where there are potential shallow-marine carbonate reservoirs equivalent to the Mississippian Leadville Limestone. These areas include the Utah-Wyoming-Montana thrust belt (Madison Limestone), the Kaiparowits Basin in southern Utah (Redwall Limestone), the Basin and Range Province of Nevada and western Utah (various Mississippian and other Paleozoic units), and the Eagle Basin of Colorado (various Mississippian and other Paleozoic units).

Many mature basins have productive carbonate reservoirs of shallow-marine shelf origin. These mature basins include the Eastern Shelf of the Midland Basin, West Texas (Pennsylvanian-age reservoirs in the Strawn, Canyon, and Cisco Formations); the Permian Basin, West Texas and southeast New Mexico (Permian age Abo and other formations along the northwest shelf of the Permian Basin); and the Illinois Basin (various Silurian units). A successful demonstration in the Paradox Basin makes it very likely that the same techniques could be applied in other basins as well. In general, the average field size in these other mature basins is larger than fields in the Paradox Basin. Even though there are differences in depositional facies and structural styles between the Paradox Basin and other basins, the fundamental use of this project’s techniques and methods is a critical commonality.

PARADOX BASIN - OVERVIEW

The Paradox Basin is located mainly in southeastern Utah and southwestern Colorado, with a small part in northeastern Arizona and northwestern New Mexico (figure 1). The Paradox Basin is an elongate, northwest-southeast-trending, evaporitic basin that predominantly developed during the Pennsylvanian. The basin can generally be divided into three areas: the Paradox fold and fault belt in the north, the Blanding sub-basin in the south-southwest, and the Aneth platform in southeasternmost Utah (figure 1). The Mississippian Leadville Limestone is one of two major oil and gas reservoirs in the Paradox Basin, the other being the Pennsylvanian Paradox Formation (figure 3); minor amounts of oil are produced from the Devonian McCracken Sandstone at Lisbon field. Most Leadville production is from the Paradox fold and fault belt (figure 2).

The most obvious structural features in the basin are the spectacular anticlines that extend for miles in the northwesterly trending fold and fault belt. The events that caused these and many other structural features to form began in the Proterozoic, when movement initiated on high-angle basement faults between 1700 and 1600 Ma (Stevenson and Baars, 1987). During Cambrian through Mississippian time, this region, as well as most of eastern Utah, was

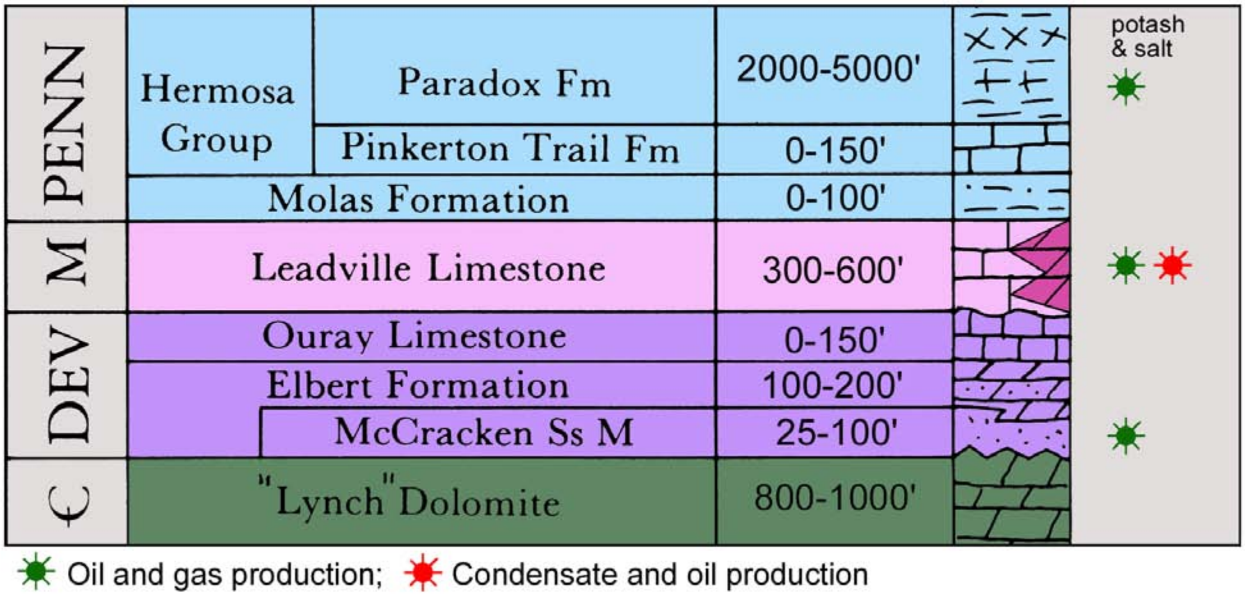


Figure 3. Stratigraphic column of a portion of the Paleozoic section determined from subsurface well data in the Paradox fold and fault belt, Grand and San Juan Counties, Utah (modified from Hintze, 1993).

the site of typical thin, marine deposition on the craton while thick deposits accumulated in the miogeocline to the west (Hintze, 1993). However, major changes occurred beginning in the Pennsylvanian. A series of basins and fault-bounded uplifts developed from Utah to Oklahoma as a result of the collision of South America, Africa, and southeastern North America (Kluth and Coney, 1981; Kluth, 1986), or from a smaller-scale collision of a microcontinent with south-central North America (Harry and Mickus, 1998). One result of this tectonic event was the uplift of the Ancestral Rockies in the western United States. The Uncompahgre Highlands in eastern Utah and western Colorado initially formed as the westernmost range of the Ancestral Rockies during this ancient mountain-building period. The southwestern flank of the Uncompahgre Highlands (uplift) is bounded by a large, basement-involved, high-angle reverse fault identified from seismic surveys and exploration drilling. As the highlands rose, an accompanying depression, or foreland basin, formed to the southwest – the Paradox Basin. Rapid subsidence, particularly during the Pennsylvanian and continuing into the Permian, accommodated large volumes of evaporitic and marine sediments that intertongue with non-marine arkosic material shed from the highland area to the northeast (Hintze, 1993).

The Paradox Basin is surrounded by other uplifts and basins, that formed during the Late Cretaceous-early Tertiary Laramide orogeny (figure 1). The Paradox fold and fault belt was created during the Tertiary and Quaternary by a combination of (1) reactivation of basement normal faults, (2) salt flowage, dissolution, and collapse, and (3) regional uplift (Doelling, 2000). Outcrops ranging in age from Pennsylvanian through Cretaceous, with surficial Quaternary deposits, are found within the Paradox Basin.

Most oil and gas produced from the Leadville Limestone is found in basement-involved, northwest-trending structural traps with closure on both anticlines and faults (figure 4). Lisbon, Big Indian, Little Valley, Lightning Draw Southeast, and Lisbon Southeast fields (figure 2) are sharply folded anticlines that close against the Lisbon or nearby fault zones. Salt Wash and Big Flat fields (figure 2), northwest of the Lisbon area, are unfaulted, east-west- and north-south-trending anticlines, respectively.

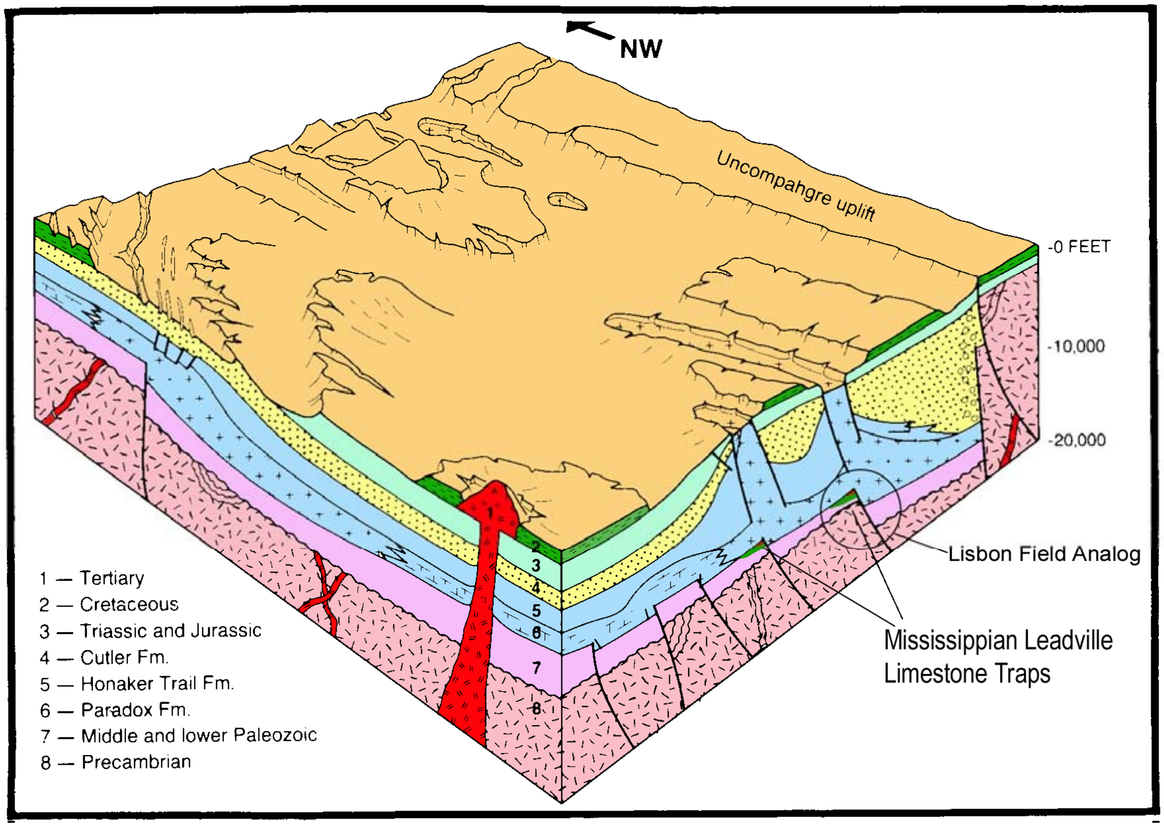


Figure 4. ***Schematic block diagram of the Paradox Basin displaying basement-involved structural trapping mechanisms for the Leadville Limestone fields (modified from Petroleum Information, 1984; original drawing by J.A. Fallin).***

SURFACE GEOCHEMICAL SURVEY IN THE LISBON CASE-STUDY FIELD AND LIGHTNING DRAW SOUTHEAST FIELD AREA, SAN JUAN COUNTY, UTAH – RESULTS AND DISCUSSION

Introduction

Surface exploration methods, such as geochemical, magnetic, and remote sensing, have increasingly proven to significantly reduce petroleum exploration risks and finding costs. These methods, and numerous case histories, are summarized by Schumacher and LeSchack (2002). Surface geochemical surveys in the Michigan and Williston Basins helped identify areas of poorly drained or by-passed oil in pinnacle reef fields (Wood and others, 2001, 2002), which are comparable in many aspects to the depositional environment of the Leadville Limestone in the Paradox Basin. Surface geochemical methods detected hydrocarbon microseepage over Grant Canyon field, Nevada, and these methods are also being used to define potential faulted, carbonate reservoirs in western Utah (Seneshen and others, 2006). Anomalies are relatively easy to identify and are conclusive about the presence of subsurface hydrocarbon deposits.

The potential for additional hydrocarbon reserves in the Paradox Basin is enormous, but the high cost of 3D seismic exploration methods in environmentally sensitive areas with extensive outcrops deters small independents from exploring for Leadville hydrocarbon reservoirs. Previous work has shown the potential of remote-sensing techniques for identifying kaolinite-enriched, bleached redbed Triassic Wingate sandstones over productive parts of Lisbon field, (figure 1) (Conel and Alley, 1985; Segal and others, 1986). These studies used Landsat Thematic Mapper (TM) data to recognize the presence of kaolinite as well as reduced iron (bleached redbeds). A ratio of TM bands 2/3 was used to define variations in ferric-iron content, while a band 5/7 ratio was used to highlight variations in clay content. Because vegetation also exhibits high band 2/3 ratio values, it can be confused with bleached rocks. Vegetation also shows high band 5/7 ratio values, which can be confused with clay-rich rocks. Other than these studies, there have been no published geochemical studies in the Lisbon field area. The UGS therefore contracted Direct Geochemical to test the effectiveness of several conventional and unconventional surface geochemical methods in the Lisbon area. The main objective in testing these techniques is to find low-cost, non-invasive geochemical exploration methods that could prescreen large areas for subsequent geophysical surveys and lease acquisition, and also act as a follow-up to classify geophysical anomalies as “productive or barren.”

The premise behind surface geochemical exploration for petroleum is that light hydrocarbons (that is, C_1 to C_5) ascend rapidly to the surface from a pressured reservoir as buoyant colloidal-size “microbubbles” along water-filled fractures, joints, and bedding planes (Price, 1986; Saunders and others, 1999). Studies over gas-storage reservoirs support the rapid development of soil-gas hydrocarbon anomalies over a charged reservoir, and the rapid depletion of such anomalies once the reservoir has been depleted (Coleman and others, 1977). Partial aerobic and anaerobic bacterial consumption of the ascending hydrocarbons produces carbon dioxide and hydrogen sulfide, which can significantly alter the chemical and mineralogical composition of overlying sediments (Schumacher, 1996). Changes to overlying sediments can include (1) adsorption of light hydrocarbons on clay particles or inclusion of hydrocarbons in secondary carbonate cements, (2) development of soil bacteria anomalies and the development of “paraffin dirt,” (3) precipitation of isotopically light calcite, pyrite, pyrrhotite, uranium, sulfur, and magnetic iron oxides, (4) bleaching of redbeds through the removal of Fe^{3+} by reduced ground water, (5) conversion of illitic clays and feldspars to kaolinite by acidic, reduced ground water, and (6) variations in the major and trace element chemistry of soil and vegetation. Chemical reactions that produce the various minerals found in “reduced chimneys” above petroleum reservoirs are shown in figure 5.

This surface geochemical study over Leadville hydrocarbon reservoirs focused on testing both “direct and indirect” methods over known “productive and non-productive areas.” Direct methods include the assessment of hydrocarbon compositional signatures of surface soils, outcrop fracture-fill soil and lichen, and 6-foot-deep (2 m) free-gas samples. Indirect methods pertain to evaluation of the inorganic compositional character of surface soils and outcrop-fracture fill soils and lichen in terms of major/trace element and anion chemistry.

Case-Study Fields

Lisbon field, San Juan County, Utah (figures 1 and 2) accounts for most of the Leadville oil production in the Paradox Basin. A wealth of Lisbon core, petrographic, and other data is

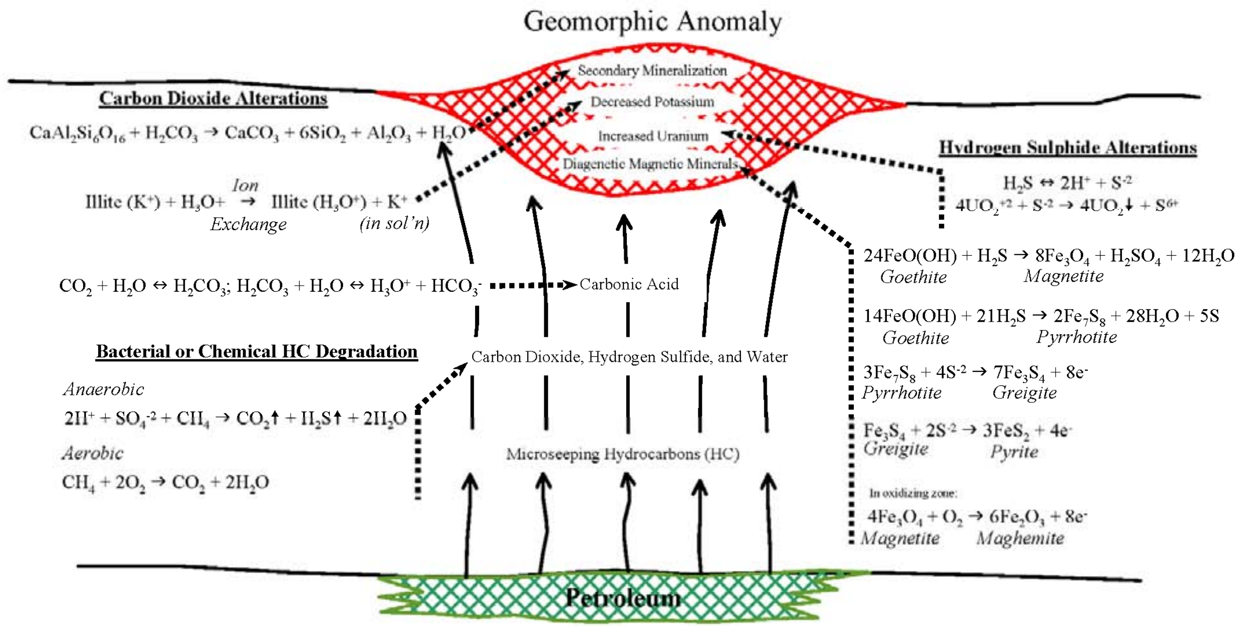


Figure 5. Model of hydrocarbon microseepage-related alteration over petroleum deposits (modified after Saunders and others, 1999).

available to the UGS. The reservoir characteristics, particularly diagenetic overprinting and history, and Leadville facies can be applied regionally to other fields and exploration trends in the Paradox Basin. A major northwest-southeast-trending anticline (tens of miles in length) along the Lisbon fault, displaces the Pennsylvanian Honaker Trail Formation against Cretaceous strata (figures 6 and 7). Therefore, we selected Lisbon as the major case-study field for the Leadville Limestone project. Four miles (6.4 km) to the southwest, the recently discovered Lightning Draw Southeast field (figures 1 and 2) its similar to Lisbon in terms of lithology (a Leadville reservoir), structure, and gas composition.

The Leadville reservoirs in Lisbon and Lightning Draw Southeast fields are separated from upper Paleozoic and Mesozoic strata by cyclic evaporites in the Pennsylvanian Paradox Formation. These conditions are typical of what might be expected when exploring for similar drilling targets in the basin. Three factors create reservoir heterogeneity within productive zones: (1) variations in carbonate fabrics and facies, (2) diagenesis (including karstification and late-stage bitumen plugging), and (3) fracturing. The extent of these factors and how they are combined affect the degree to which they create barriers to fluid flow.

Lisbon field is ideal for a surface geochemical survey. Besides active hydrocarbon production from beneath the easily accessible area, the surface geology is similar to the subsurface structure of the field (figures 6, 7, and 8). In addition, Lightning Draw Southeast field is also accessible and is at or near original reservoir pressure making it an excellent test site to evaluate hydrocarbon seepage in comparison with that at Lisbon.

Lisbon Field Synopsis

The Lisbon trap is an elongate, asymmetric, northwest-trending anticline, with nearly 2000 feet (600 m) of structural closure and bounded on the northeast flank by a major, basement-involved normal fault with over 2500 feet (760 m) of displacement (Smith and

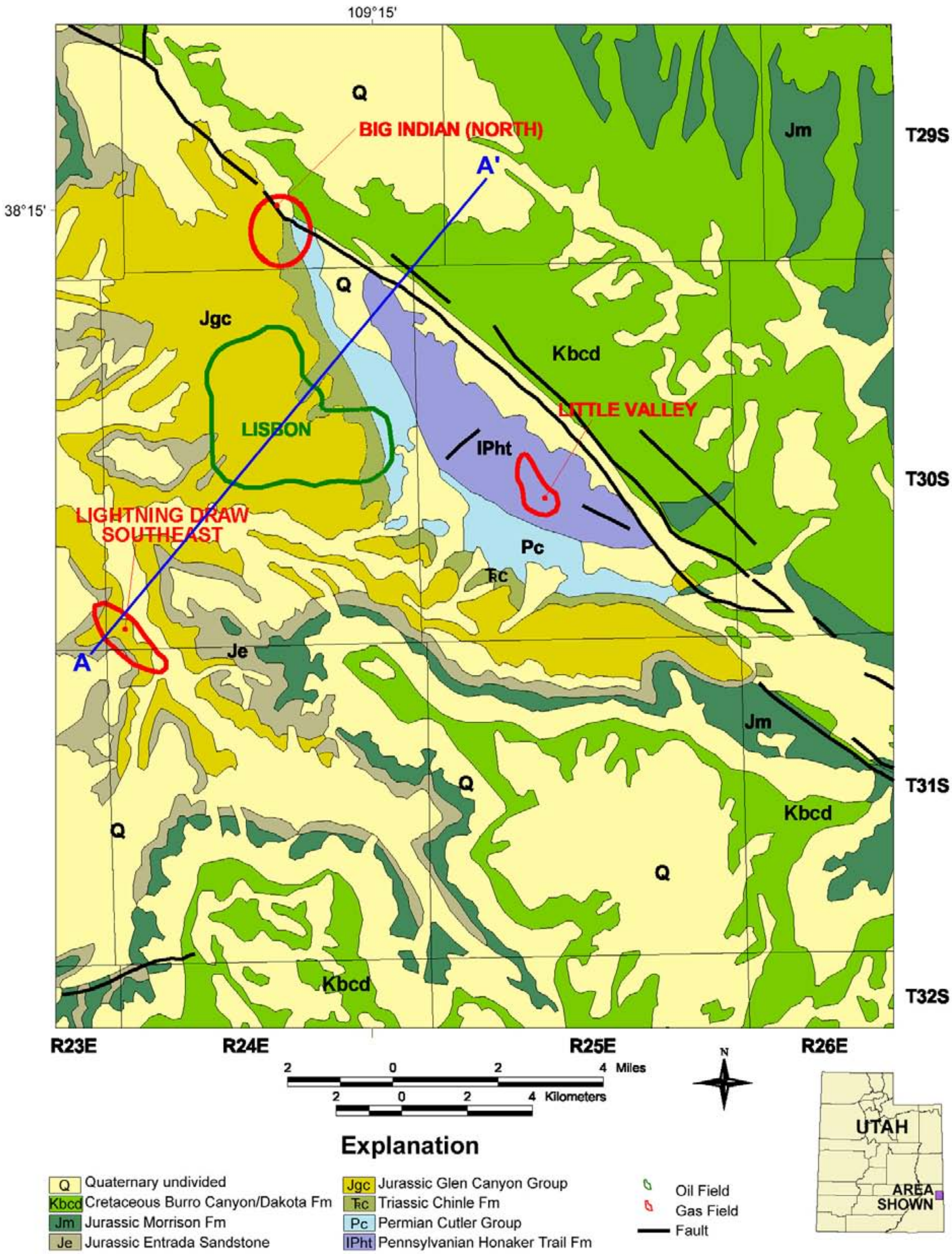


Figure 6. General surface geology of the Lisbon field area (modified from Hintze and others, 2000) with location of cross section A-A'.

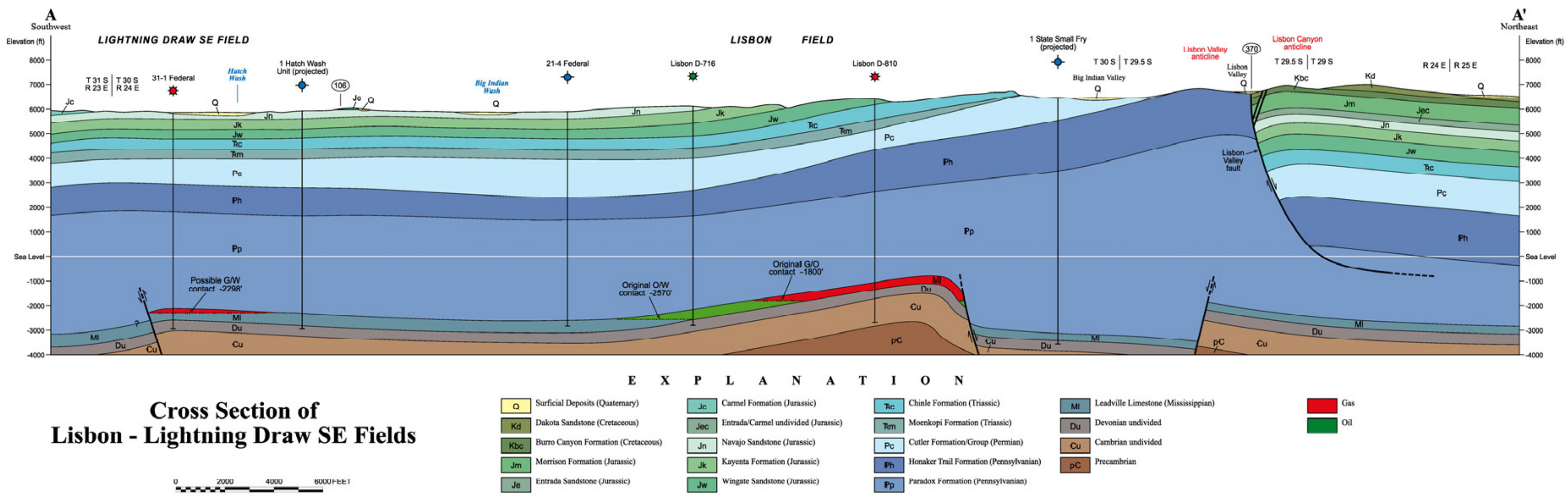


Figure 7. Cross section through the Lisbon and Lightning Draw Southeast fields showing the fault-bounded Leadville Limestone hydrocarbon reservoirs.

A

B

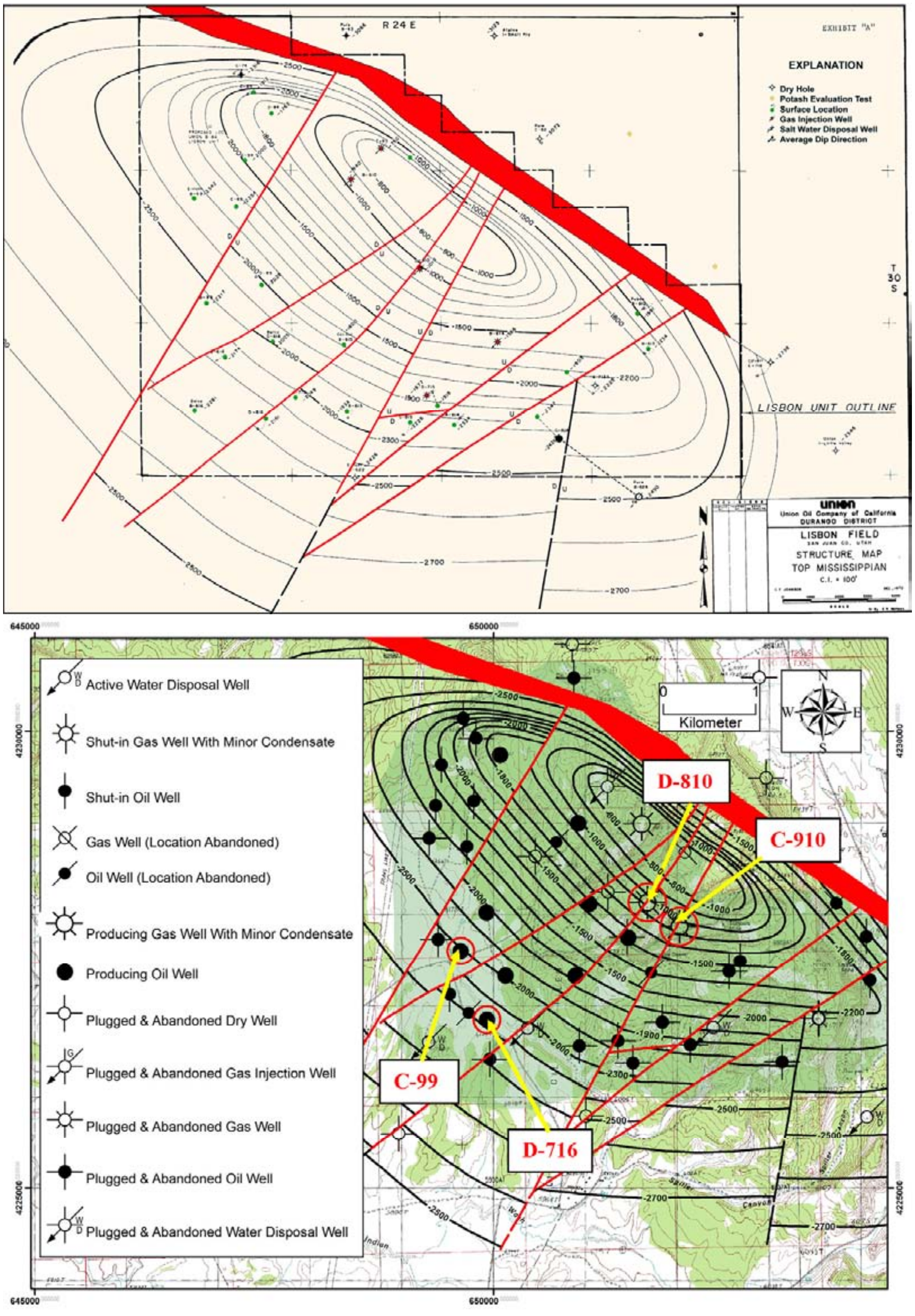


Figure 8. A – Top of structure of the Leadville Limestone, Lisbon field, San Juan County, Utah (modified from C.F. Johnson, Union Oil Company of California files, 1970; courtesy of Tom Brown, Inc.). B – Top of structure of the Leadville Limestone superimposed over the topographic base, well locations (well sites identified where detailed sampling was conducted), and Lisbon oil field outline (shaded bluish green). Base map: La Sal 30' X 60' topographic quadrangle map, U.S. Geological Survey.

Prather, 1981) (figures 7 and 8). Several minor, northeast-trending normal faults divide the Lisbon Leadville reservoir into segments (figure 8).

Producing units in Lisbon field contain dolomitized crinoidal/skeletal grainstone, packstone, and wackestone fabrics. Diagenesis includes fracturing, autobrecciation, karst development, hydrothermal dolomite, and bitumen plugging. The net reservoir thickness is 225 feet (69 m) over a 5120-acre (2100 ha) area (Clark, 1978; Smouse, 1993). Reservoir quality is greatly improved by natural fracture systems associated with the Paradox fold and fault belt. Porosity averages 6% in intercrystalline and moldic networks enhanced by fractures; permeability averages 22 millidarcies (mD). The drive mechanism is an expanding gas cap and gravity drainage; water saturation is 39% (Clark, 1978; Smouse, 1993). The bottom-hole temperature ranges from 133 to 189ºF (56-87ºC).

Lisbon field was discovered in 1960 with the completion of the Pure Oil Company No. 1 NW Lisbon USA well, NE1/4NW1/4 section 10, T. 30 S., R. 24 E., Salt Lake Base Line and Meridian (SLBL&M) (figure 8), with an initial flowing potential (IFP) of 179 bbls of oil per day (BOPD) (28 m^3) and 4376 thousand cubic feet of gas per day (MCFGPD [124 MCMPD]). The original reservoir field pressure was 2982 pounds per square inch (psi [20,560 kPa]) (Clark, 1978). There are currently 20 producing (or shut-in wells), 13 abandoned producers, five injection wells (four gas injection wells and one water/gas injection well), and four dry holes in the field. Cumulative production as of February 1, 2007, was 51,153,440 bbls of oil (8,133,397 m^3), 790.6 billion cubic feet of gas (BCFG [22.4 BCMG]) (cycled gas), and 50,242,881 bbls of water (BW [7,988,618 m^3]) (Utah Division of Oil, Gas and Mining, 2007). Gas that was re-injected into the crest of the structure to control pressure decline is now being produced. The composition of produced gas from the Lisbon gas cap and oil leg is given in table 1.

Table 1. Produced gas compositions (weight percent) from Lisbon and Lightning Draw Southeast fields.

	Lisbon Gas Cap		Lisbon Oil leg		Lightning Draw Southeast Gas	
Well No.	**D-810**	**C-910**	**C-99**	**D-716**	**Federal 1-31**	**Evelyn Chambers Gov. 1**
Daily Production* (May 2006)	2.3 MMCFGPD	7 MMCFGPD	10 BOPD	8 BOPD	1.5 MMCFGPD, 18 BOPD	0.3 MMCFGPD, 8 BOPD
Methane	36.16	38.28	37.83	40.27	27.01	23.97
Ethane	7.44	8.39	8.87	8.63	4.85	3.90
Propane	2.76	2.45	4.88	4.40	3.26	2.59
Isobutane	0.48	0.40	0.93	0.83	0.71	0.60
Normal Butane	0.26	0.21	0.48	0.45	0.40	0.34
Isopentane	0.29	0.22	0.55	0.51	0.50	0.41
Normal Pentane	0.35	0.27	0.67	0.62	0.58	0.46
Carbon Dioxide	23.58	28.78	30.89	27.69	27.02	36.64
Hydrogen Sulfide	1.37	1.00	0.20	0.28	0.00	0.00
Nitrogen	25.97	18.85	13.18	14.66	33.48	29.20
Helium	0.70	0.66	0.53	0.66	1.42	1.40
Hexanes+	0.62	0.50	0.99	1.00	0.77	0.48
Total	99.97	100.00	100.00	100.00	100.00	100.00

* MMCFGPD = million cubic feet of gas per day, BOPD = barrels of oil per day

Lightning Draw Southeast Field Synopsis

Like the Lisbon trap, the Lightning Draw Southeast trap is also an elongate, but relatively small, asymmetric, northwest-trending anticline (no surface expression), with nearly 250 feet (75 m) of structural closure. However, the structure is bounded on the southwest flank by a high-angle, basement-involved reverse fault (figures 7 and 9). A northwest-trending syncline separates the Lightning Draw Southeast and Lisbon anticlines in the subsurface. The field consists of two productive wells, primarily gas and condensate, along with barren dry wells off structure (figure 9).

Producing units are similar to Lisbon field in terms of depositional environments, carbonate fabrics, and diagenesis. There are two principal Leadville zones at Lightning Draw Southeast field: an upper zone primarily of fossiliferous limestone with crinoids, brachiopods, and coated grains forming skeletal wackestone to packstone and some grainstone fabrics; and a lower zone of dolomitized mudstone with large rhombic to sucrosic dolomite crystals. Diagenesis consists of hydrothermal dolomitization, bitumen coating, and fracturing. The producing interval is confined to the upper zone although both have porosity units over 6 percent. The net reservoir thickness is about 40 feet (12 m) over an approximate 320-acre (130 ha) area. Porosity over the perforated interval averages 17%, and permeability averages 13 mD. The drive mechanism is an expanding gas cap; water saturation is 21%. The bottom-hole temperature is 136ºF (58ºC).

The Leadville Limestone reservoir at Lightning Draw Southeast field was discovered in 2004 with the completion of the ST Oil Company Federal No. 1-31 well, NW1/4SW1/4 section 31, T. 30 S., R. 24 E., SLBL&M (figures 7 and 9), with an IFP of 18 bbls of condensate per day (BCPD [3 m^3]), 1543 MCFGPD (44 MCMPD), and 5 BW per day (0.8 m^3) (production from the Pennsylvanian Paradox Formation [Ismay zone] was established in 1980 by Texaco). The API gravity of the condensate is 50º. The original reservoir field pressure was 1100 psi (7585 kPa). There is currently one producing and one shut-in gas/condensate well in the field. Cumulative production as of February 1, 2007, was 1791 bbls of condensate (285 m^3), 179,704 MCFG (5089 MCMG), and 1446 BW (230 m^3) (Utah Division of Oil, Gas and Mining, 2007). In comparison with the Lisbon field, the produced Lightning Draw Southeast gas contains fewer hydrocarbons by more nitrogen and helium (table 1).

Methodology for the Geochemical Survey

Collection of Surface Soils

Two surface soil types are evident in the study area. In outcrop-rich areas (shown as Mesozoic and Paleozoic geological units on figure 10), the thin soils that sporadically cover bedrock are classified as Rizozo-Rock Outcrop-Ildefonso types (see general soil map of the Canyonlands area [Lammers, 1991]). The dominant vegetation on these thin soils is piñon, Utah juniper, big sagebrush, Mormon tea, and galleta. Shallow Rizozo soils, which formed from residual and eolian deposits, are a yellowish-red, gravelly, fine-grained, sandy loam. Samples collected from 8 to 12 inches (20-30 cm) are reddish-brown, sandy loam, clay loam and fine-grained sandy loam (figure 11). In broader valleys (eolian and alluvium deposits on Figure 10), there is a mixture of Begay-Windwhistle-Ildefonso soil types. Vegetation is primarily big sagebrush, spiny hopsage, snakeweed, and blue grama. These soils form on alluvium and eolian deposits derived mainly from sandstones and at surface consist of reddish-

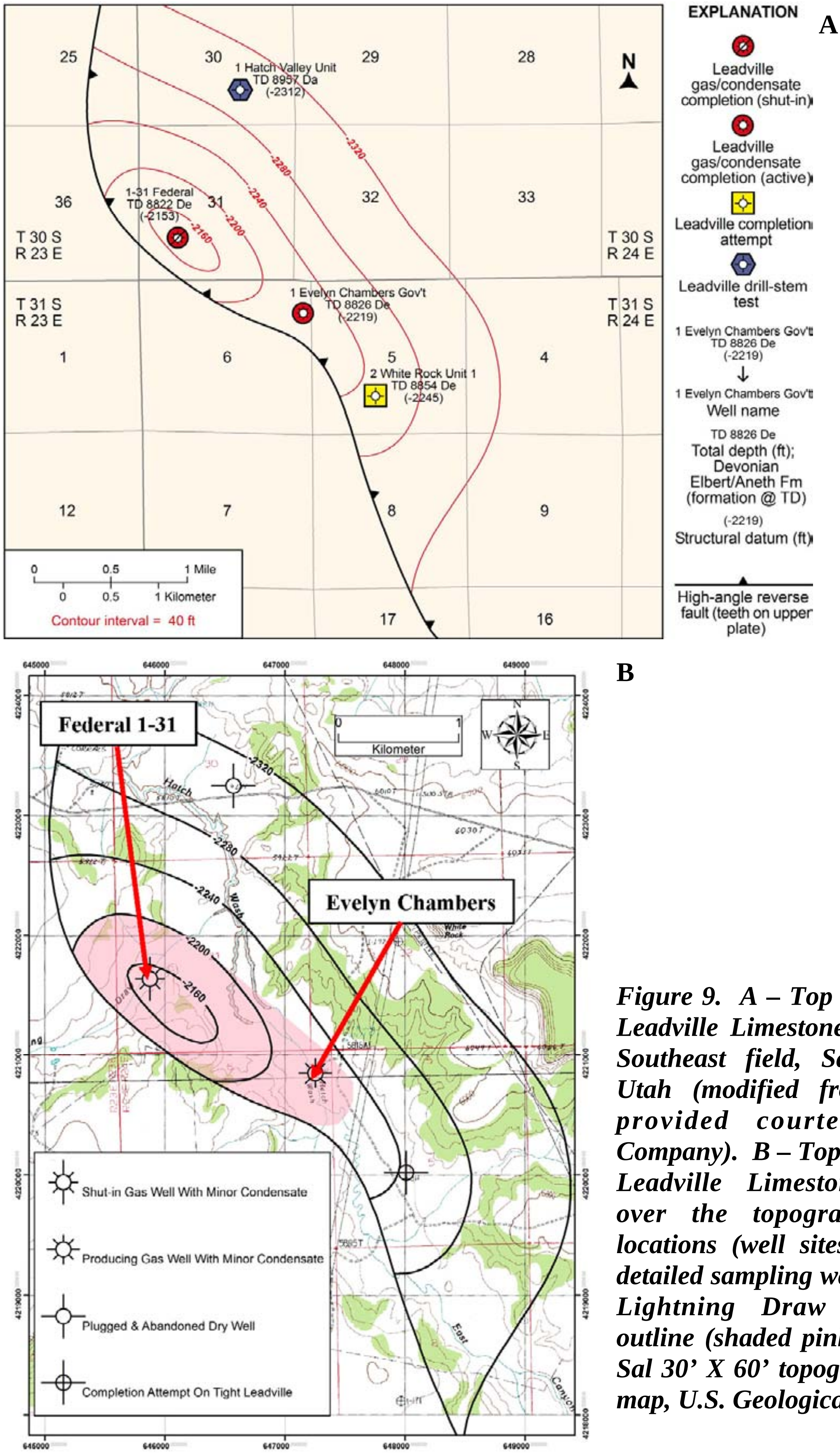


Figure 9. A – Top of structure of the Leadville Limestone, Lightning Draw Southeast field, San Juan County, Utah (modified from a fault map provided courtesy of ST Oil Company). B – Top of structure of the Leadville Limestone superimposed over the topographic base, well locations (well sites identified where detailed sampling was conducted), and Lightning Draw Southeast field outline (shaded pink). Base map: La Sal 30' X 60' topographic quadrangle map, U.S. Geological Survey.

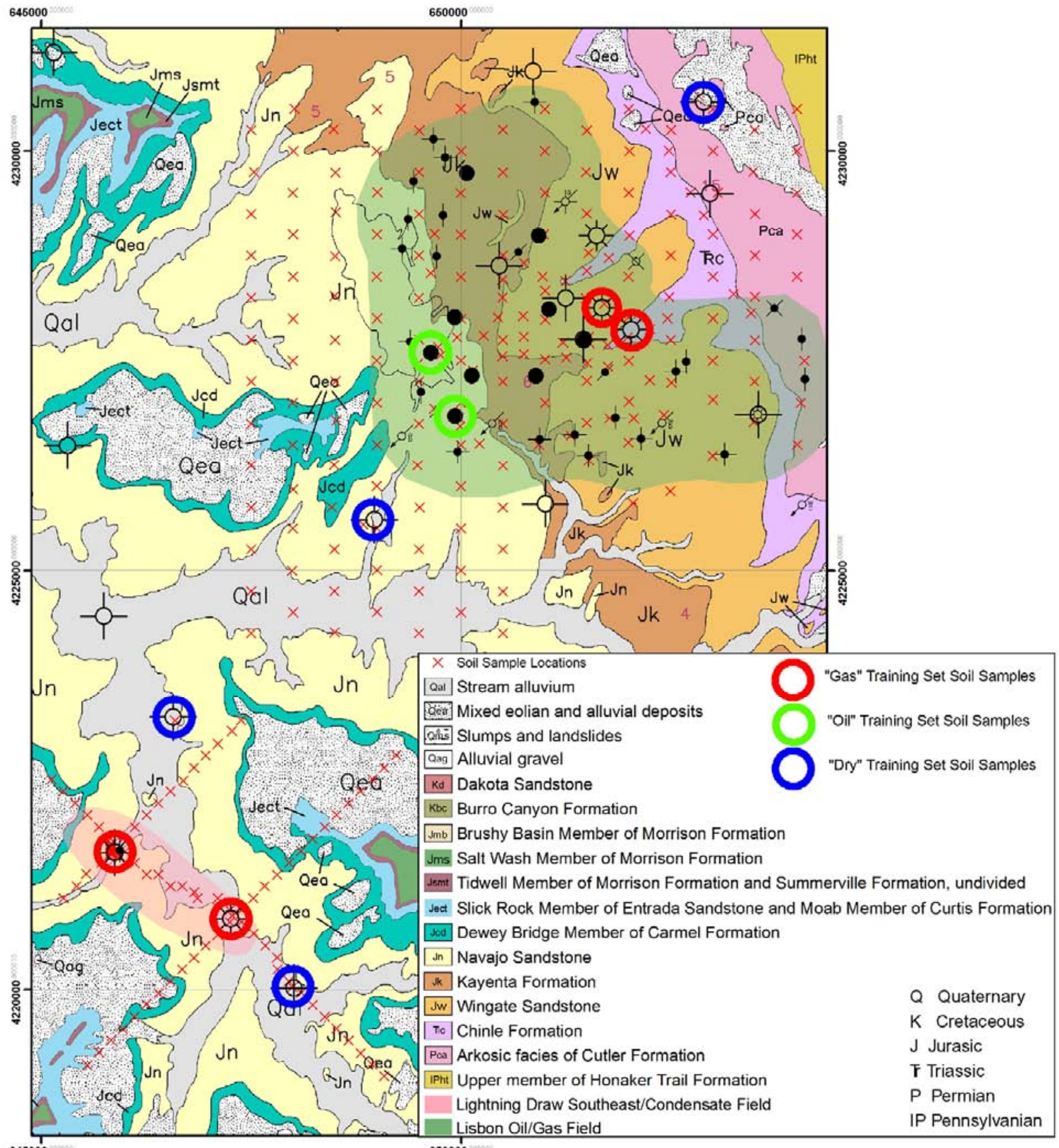


Figure 10. Distribution of grid, line, and training set soil samples collected over and around the Lisbon and Lightning Draw Southeast fields, superimposed over geologic map modified from Doelling (2005); see figure 8 for explanation of well symbols.

Figure 11. Collection of reddish-brown, fine sandy loam soils from outcrop areas. These samples are referred to as "surface soils" throughout this report.

brown fine sandy loam. Subsoils collected from 8 to 12 inch (20-30 cm) depth are yellowish-red loamy fine-grained sand.

Surface soil samples (n = 322) were collected at 1500-foot (500 m) intervals on a 16-square-mile (42 km^2) rectangular grid over and around the Lisbon field (figure 10). The survey was then expanded to include the collection of 78 soils at 656-foot (200 m) intervals on a grid of northwest-southeast and northeast-southwest lines over Lightning Draw Southeast field. The sample intervals chosen were based on the size of the fields themselves. The sampling grid and lines extend well beyond the proven limits of Lisbon and Lightning Draw Southeast fields to ensure adequate background data. The areas chosen therefore sufficiently cover the gas caps, oil leg (present only at Lisbon), and background "barren" areas. In addition, samples were collected around gas, oil, and dry wells (15 samples around each) for analogue matching purposes and the development of a discriminant model for Lisbon and Lightning Draw Southeast fields (figure 10).

Along the grid and lines, shallow (generally 8- to 12-inch [20-30 cm] deep) soil samples were collected with a spade or tree-planting shovel over a 6-foot area (2 m) at each site (figure 11). Care was taken to avoid sampling material sluffed off the surface. The soils were placed and stored in airtight, Teflon-sealed glass soil jars to prevent hydrocarbon contamination during transport to the laboratory. In addition to the jar samples, soils were also collected in plastic Zip-loc bags for major/trace element and anion analyses. Some sample sites had to be offset because of lack of soil in outcrop areas. Evidence of surface alteration that could be attributed to hydrocarbon seepage and fracturing was also noted. Sample sites around wells were located topographically high relative to the well pad to reduce the possibility of contamination.

Collection of Outcrop Fracture-Fill Lichen, Mosses, and Soil

Joints in outcrops may provide pathways for hydrocarbon microseepage to the surface, which may be evident in the soils and vegetation that fill the joints (figures 12 and 13). Thus, the sampling program was further expanded to collect sand and soil samples (33 samples) from the joints for additional hydrocarbon and elemental analysis over barren and productive parts of both Lisbon and Lightning Draw Southeast fields (figure 14).

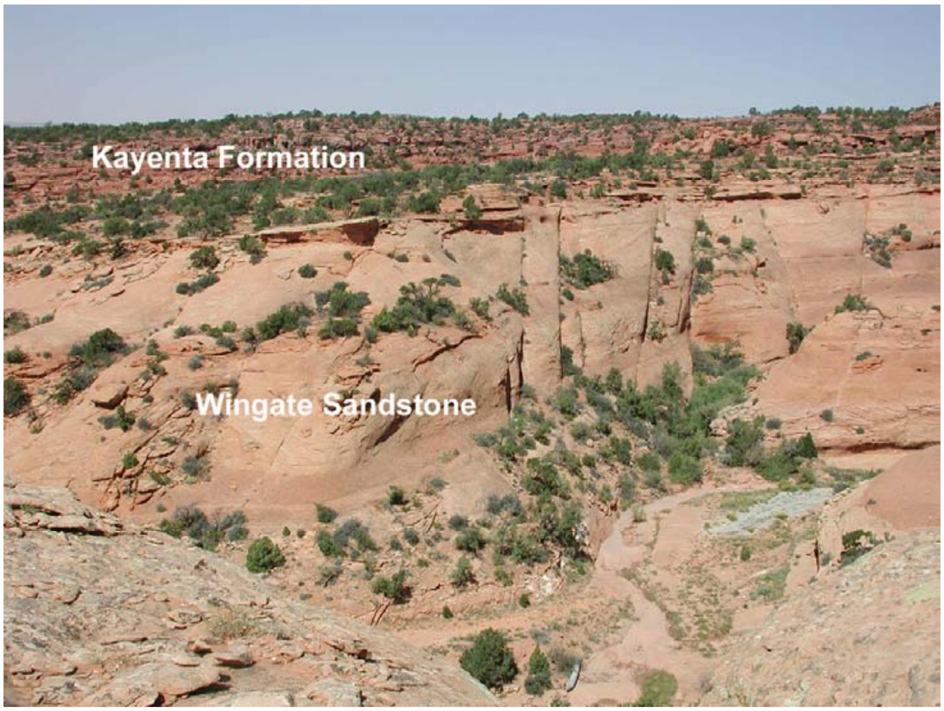


Figure 12. Photograph from the Lisbon field of a sharp contact between the Jurassic Wingate Sandstone and Kayenta Formation. Note the subvertical joints in the Wingate Sandstone.

Jointing is best developed in the Jurassic Wingate and Navajo Sandstones, and is also present in the intervening Kayenta Formation although it is not as pronounced (figure 12). Joints may be thin (millimeter to centimeter) or several feet in width and tens of feet or miles in length. They may also occur as parallel (figure 12) or curvilinear polygonal sets, often with several orders of size or generation (figure 13). Joint sets in the area generally are vertical to near vertical. Many small joints contain very little soil, although enough to support bryophytes and lichen growth where there is sufficient moisture.

In the Lisbon field area, joint orientation in the Wingate Sandstone on the southwest-dipping flank of the Lisbon surface anticline and over the gas cap is dominantly northwest-southeast (figure 14), parallel to the regional structural trends. In the relatively flat-lying Navajo Sandstone farther southwest of the surface structure and over the oil leg, the dominant joint trend is nearly perpendicular, east-northeast - west-southwest, to the orientation over the gas cap (figure 14). Joint sets in flat-lying Navajo over the water leg southwest of the field display a dominant east-west orientation (figure 14).

Figure 13. Bryophytes and lichen along curvilinear polygonal joints in Navajo Sandstone over the water leg of Lisbon field.

In the Lightning Draw Southeast field area, the Navajo Sandstone is also relatively flat lying. Two sets of joints are found near the Federal No. 1-31 well. Their orientations are generally north-south and northwest-southeast (figure 14). Two joint sets are also found in the Navajo to the southeast near the Evelyn Chambers Government No. 1 well with orientations trending northwest-southeast and northeast-southwest.

Soil samples from joints required the same amount of sample material as was taken along the grid, but they were harder to acquire. Representative samples were often only obtained by scraping sandy soil out of the joints with a stainless steel spoon, knife, or flathead screwdriver. Where the joints were narrow and the soil zone especially shallow, this process frequently required sampling along tens of feet in order to acquire enough material. Joints with established vegetation generally have deeper soils and better sampling opportunities.

Bryophytes (mosses) and lichen commonly grow along thin joints in the area where there are higher than ambient amounts of moisture. These plants may also show a geochemical signature in their tissues indicative of hydrocarbons or subsurface mineralization, so they were also sampled (30 samples) to compare with the soil analysis results. Two species of bryophytes and one species of lichen grow along joints in the area. The bryophytes fit into the genera *Grimmia* (possibly *Grimmia wrightii*) and *Bryum*. Both are common soil crust mosses. The lichen is *Collema tenax* – an abundant and common soil crust lichen in the intermountain western United States (Larry St. Clair, Monte L. Bean Life Science Museum, Brigham Young University, written communication, October 28, 2006).

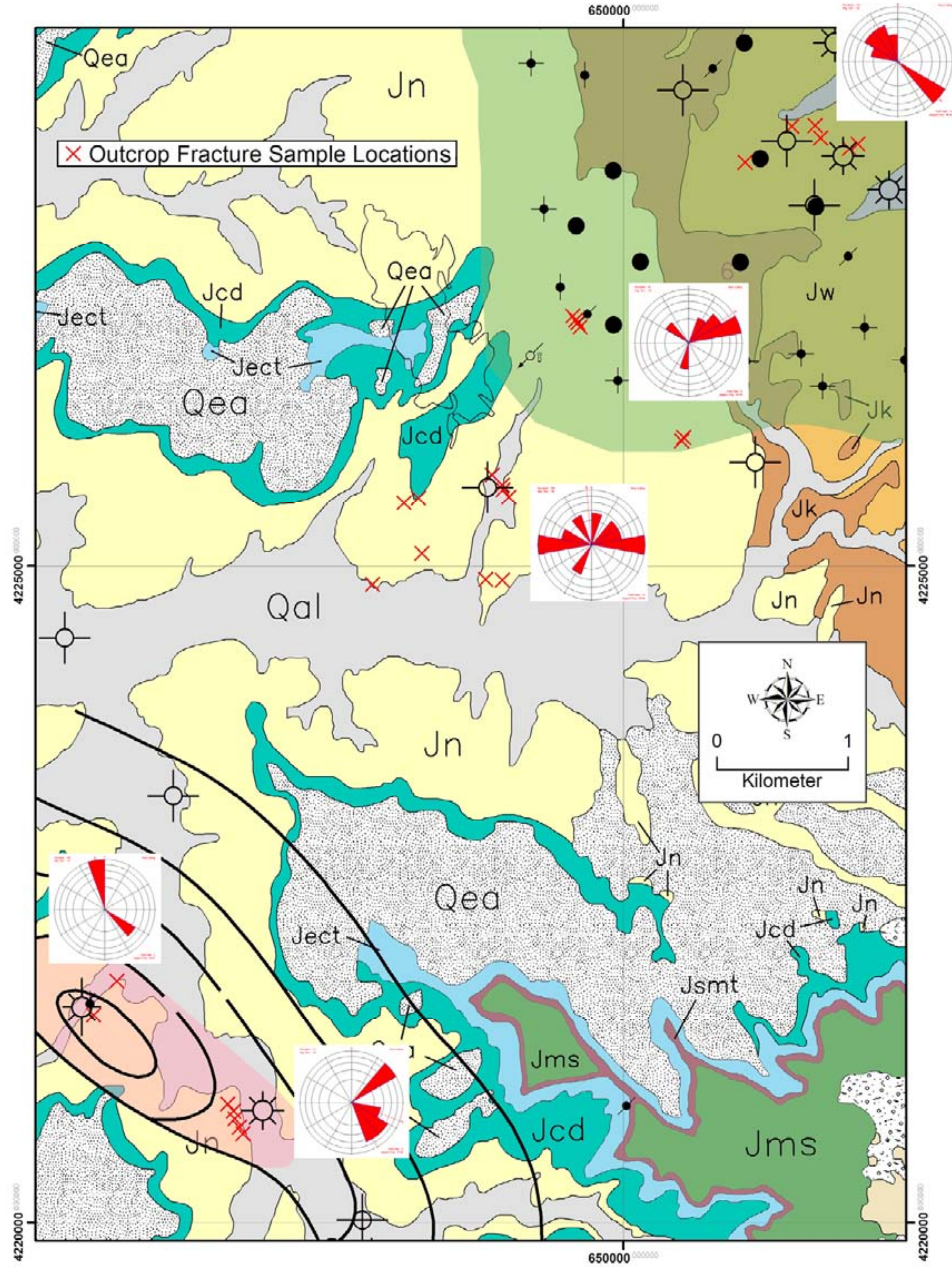


Figure 14. Outcrop fracture-fill lichen and soil sample locations over the Lisbon gas cap, oil leg, and water leg, and over the Lightning Draw Southeast field (shown in pink). Dominant joint orientations at sample site areas are also indicated. Surface geology modified from Doelling (2005); see figures 8 and 10 for explanations of well symbols and geologic units. Form line contours based on top of structure of the Leadville Limestone shown on figure 9.

Collection of 6-Foot-Deep Free-Gas Samples

Free-gas samples were collected at 15- to 300-intervals (5-100 m) over the Lightning Draw Southeast field and in off-structure areas using the following protocol (Figure 15):

1. Drill to at least a 6-foot (2 m) depth (10 feet [3 m] preferably) in unconsolidated overburden using the Geoprobe percussion (hammer) drill with 1-inch diameter pipe (figure 15).

2. Insert polyethylene tubing into rod and secure it to a retractable point at the bottom of the pipe.

3. Purge the soil air at least three times to clear the tubing of ambient air using a plastic 40 cc syringe (figure 15).

4. Draw soil air (free gas) up using the syringe and force it into a 1-liter Tedlar bag (for hydrocarbon and fixed gas analyses) and/or lead-lined CO_2 cartridge (for helium analysis).

All sample site location coordinates were recorded in the field notes and marked on a Global Positioning System (GPS). Prior to the survey, all sample site coordinates were generated in Garmin™-compatible format for uploading to the GPS. The sample design for the survey was digitized on topographic maps using Surfer™.

Laboratory Analysis

The soil, bryophytes, and lichen samples were dried, sieved to <63 microns, thermally desorbed at constant temperature for constant time, and the headspace gas was analyzed for 38 hydrocarbon compounds in the C_l to C_{12} range (table 2). Organic carbon in the samples was estimated using a gravimetric technique (loss on ignition).

In addition, a solvent extract of sieved soil splits was analyzed by synchronous scanned fluorescence (SSF), which measures relative amounts of heavy (C_6 to C_{40}) aromatic hydrocarbons. Synchronous scanning fluorescence technique is a very cost-effective way to analyze soils for traces of the much heavier liquid hydrocarbons without the high cost of elaborate extraction techniques and high-resolution gas chromatography. Soil/sediment samples are dried at low temperature, disaggregated, and sieved for the fine (clay and silt) fraction. A portion of the sample is weighed into a test tube and measured volumes of a spectral grade solvent mixture (D99) is added. The tubes are capped, agitated to complete the extraction, and centrifuged to separate the particulates from the solvent extract. The extract is pipetted into a quartz cuvette for analysis in an Ultraviolet-SSF Spectrophotometer. The sample is scanned from wavelengths of 250 to 500 nm. The hydrocarbons that fluoresce in oils are the ringed aromatic compounds, which can be grouped by the number of (benzene type) rings chained together. These groups have fluorescence spectra maxima that increase in wavelength approximately with increasing ring numbers, as shown in figure 16.

Splits of the dried and sieved soil samples were also dissolved in aqua regia acid and the supernatant was analyzed for 53 major/trace elements by inductively-coupled-plasma mass and

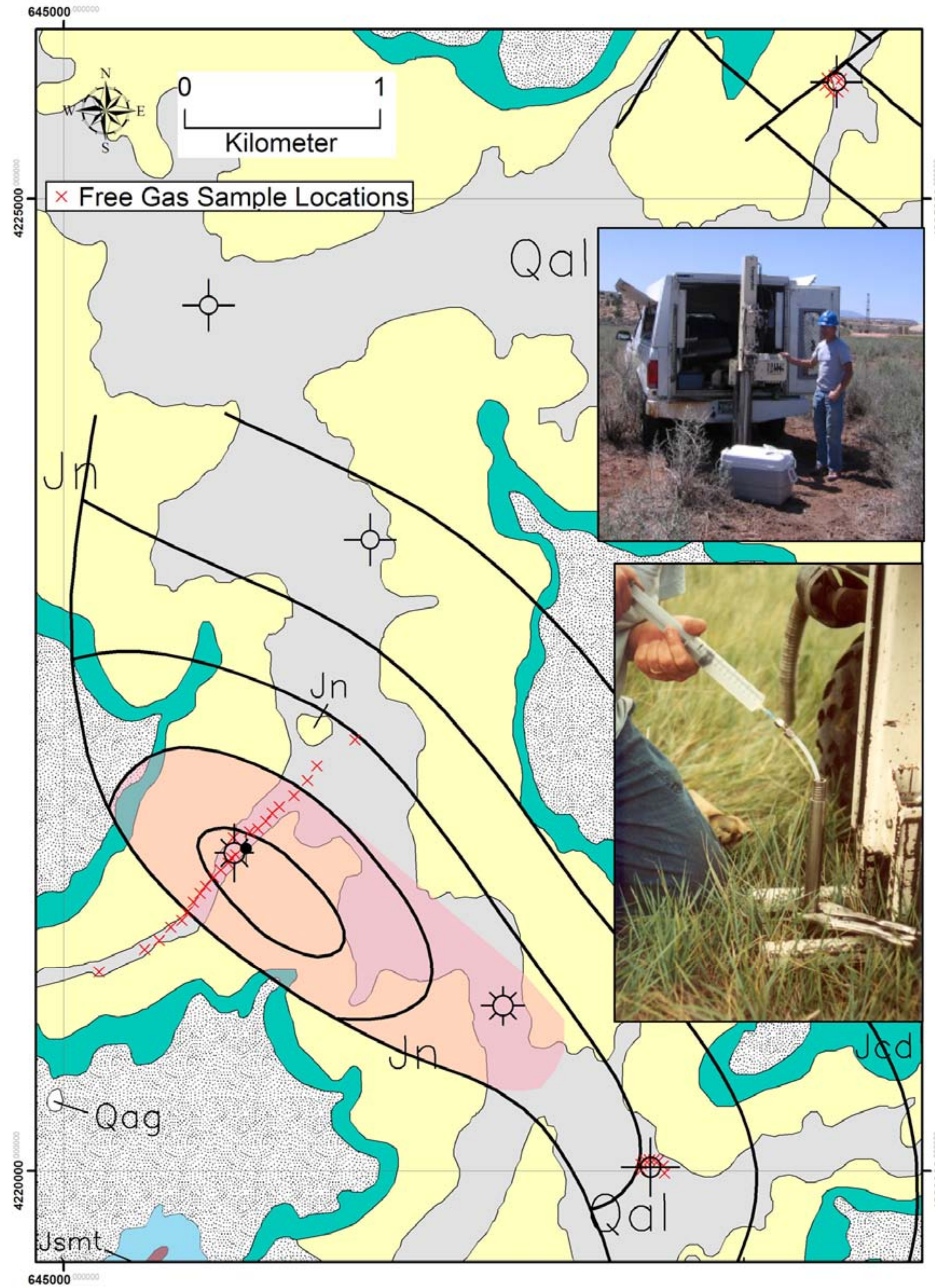


Figure 15. Location of 6-foot-deep free-gas samples over and off Lightning Draw Southeast field (shown in pink). The samples were collected with a Geoprobe "Direct-Push" drill, and gas was extracted through plastic tubing (inset photos), which was inserted into the 1-inch steel pipes. Surface geology modified from Doelling (2005); see figures 8 and 10 for explanations of well symbols and geologic units. Form line contours based on top of structure of the Leadville Limestone shown on figure 9.

Table 2. Components reported by four analytical methods.

C_1-C_{12} Hydrocarbons	Seven Anions	53 Major and Trace Elements	Synchronous Scanned Fluorescence
methane, ethane, ethene, propane, propene, i-butane, n-butane, butene, i-pentane, n-pentane, pentene, i-hexane, n-hexane, hexene, i-heptane, n-heptane, heptene, i-octane, n-octane, benzene, n-butylbenzene, cyclohexane, n-decane, n-dodecane, ethylbenzene, m-ethyltoluene, p-ethyltoluene, indane, naphthalene, n-nonane, n-propylbenzene, 1,2,4,5-tetramethylbenzene, toluene, 1,2,4-trimethylbenzene, 1,3,5-trimethylbenzene, n-undecane, m-xylene, p-xylene, and o-xylene.	fluoride, chloride, bromide, nitrite, nitrate, phosphate, sulfate	Ag, Al, As, Au, B, Be, Bi, Ca, Cd, Ce, Co, Cr, Cs, Cu, Fe, Ga, Ge, Hf, Hg, I, In, K, La, Li, Mg, Mn, Mo, Na, Nb, Ni, P, Pb, Pd, Pt, Rb, Re, S, Sb, Sc, Se, Sn, Sr, Ta, Te, Th, Ti, Tl, U, V, W, Y, Zn, Zr	Fluorescence intensities in the 250 to 500 nm range that correspond to condensate, medium-gravity oil, and low-gravity oil. Allows fingerprint matching with produced oils in the area.

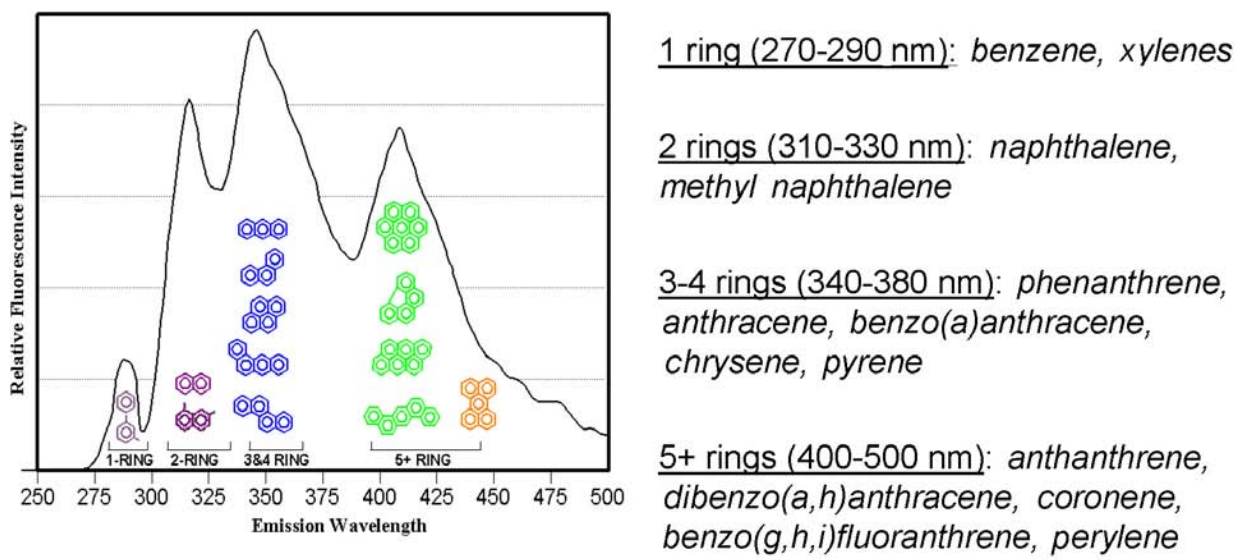


Figure 16. Schematic of synchronous scanned fluorescence spectra depicting the aromatic hydrocarbons and corresponding emission wavelengths.

emission spectrometry (ICP/MS and ICP/ES). Samples were also analyzed for seven anion species using a deionized water extraction and ion chromatography.

The free-gas samples are drawn from the Tedlar bag with a 5-cc syringe and analyzed for 19 hydrocarbons in the C_1 to C_8 range using a gas chromatograph with a flame ionization detector (GC-FID). Carbon dioxide, CO, O_2, N_2, and H_2 are analyzed using a gas chromatograph with a thermal conductivity detector (GC-TCD). Gas from the lead-lined cartridges is analyzed for helium using a micro-TCD.

The precision and accuracy of the hydrocarbon, organic carbon, major/trace element, and anion analyses was between ±10 to 20% based on a 95% confidence level based on the analysis of laboratory duplicates and standard reference materials at 10% frequency.

Interpretation and Mapping

The organic and inorganic data were compiled in an Excel spreadsheet for interpretation. The hydrocarbon and elemental composition of near-surface soil gas and soils can reflect the character of subsurface petroleum accumulations and faults. It is important to identify and correlate the numerous near-surface compounds and elements with their sources—particularly petroleum accumulations. Different accumulations yield different near-surface compositional signatures, which can be used to determine if the accumulation is in the oil or gas range. Factor and discriminant analysis were used in this study to reduce the complex mixtures of organic and inorganic variables to a smaller number of interpretable variables.

Both factor and discriminant analysis are multivariate statistical tools that allow the evaluation of large numbers of data variables simultaneously. The use of these multivariate tools permits the user to appreciate the existence of particular organic and inorganic associations that may reflect microseepage and mineralizing processes. In oil and gas exploration, this is important because the presence of oil or gas in the subsurface is rarely imaged by one or two variables.

Factor analysis summarizes the data set in a series of mathematical "vectors" or "factors," which are combinations of co-varying variables in multivariate space. The derived factors (when combined together) account for all or most of the variation in the dataset, but in fewer variables than are in the data set. For example, there may be 15 variables measured in a dataset, but these may be reduced to five factors, which account for most of the variance in the individual variables. Factors are ranked in descending order of the amount of variance they account for in the dataset. Factor 1 accounts for the most variance, factor 2 the second greatest, and so on. For each factor, it is possible to identify the mixture of variables (components) and their relative importance. In oil and gas producing basins, it is common for factor analysis to result in at least one factor reflecting a mixture of light (C_1 to C_4) hydrocarbons (that can be related to "gas"), and at least one reflecting a mixture of heavy (C_5 to C_x) hydrocarbons (that can be related to "oil"). Factor loadings are the correlation coefficients between the variables and the factors. The more a variable is correlated with a particular factor (that is, correlated group of variables in multivariate space), the higher the factor loadings will be for that variable. Factors are plotted spatially as "factor scores," which represent the degree of correlation of variables in particular samples with the derived factors.

Forward stepwise discriminant analysis is used to discriminate the compositional character of microseepage over productive and barren areas using the variables from soil samples over known productive and barren areas (that is, training sets). In the case of soil samples, the compositional character of the "adsorbed" microseepage over dry and barren areas reflects an alteration effect on soils as a result of continuous or episodic microseepage over long periods of time. In essence, discriminant analysis is used to distinguish between the unique multicomponent alteration signature imparted to soils over barren and productive areas from prolonged microseepage. The analysis derives a "discriminant function" or linear combination of organic variables that separates the compositional character of microseepage between "productive and barren" areas. The form of the discriminant function, also called a *canonical root*, is a latent variable which is created as a linear combination of discriminating (independent) variables, such that $L = b_1x_1 + b_2x_2 + ... + b_nx_n + c$, where the b's are discriminant coefficients, the x's are discriminating variables, and c is a constant. The discriminant coefficients are used to assess the relative classifying importance of the independent variables.

If microseepage can be distinguished between "productive and barren" areas based on statistical significance tests (Wilks' lambda) and cross-validation, then the discriminant function can be used to classify samples from "unknown" areas into productive or barren categories. These predictions are represented as discriminant scores or probabilities of a particular sample falling into either barren or productive clusters.

In some cases, the absolute concentrations of organic and inorganic variables in soils and free gas can be spatially correlated with underlying hydrocarbon reservoirs, and may actually reflect charge in the reservoir rather than an "alteration-effect" on soils as a result of hydrocarbon microseepage over long periods of time. In the Lisbon field case study, absolute concentrations of organic and inorganic variables have been transformed to Z-scores to better evaluate contrast in the data. The Z-scores are derived by subtracting the population mean for a particular variable from the concentration of that variable for a particular sample and then dividing by the population standard deviation. This reduces the data to a mean of zero and the Z-scores then represent standard deviations above a mean of zero. In this study, the absolute concentrations of organic and inorganic variables over Lisbon field were significantly higher than those over the Lightning Draw Southeast field because of more intense seepage and/or surface contamination over Lisbon and the presence of exposed uranium mineralization. Z-scores were therefore calculated separately for the Lisbon and Lightning Draw Southeast datasets to more fully appreciate the subtle, but significant anomalies at Lightning Draw Southeast. The absolute concentrations of hydrocarbons and fixed gases in free gas over Lightning Draw Southeast are plotted, however, to emphasize the low concentration of species in these samples.

Organic and inorganic variables, and the factor and discriminant scores from linear combinations of variables, were plotted on a geological background as proportional symbols using ArcGIS 9.1™. Only those variables and scores that show a spatial correlation with Lisbon and/or Lightning Draw Southeast fields are presented here. There are several inorganic variables, for instance, that are spatially correlated with specific geological units, the meaning of which, is beyond the scope of this study.

Results of the Geochemical Survey

Hydrocarbon and Fixed Gas Results

The results of the study show that the shallow surface geochemical methods tested are capable of discriminating between barren and productive parts of Lisbon and Lightning Draw Southeast fields. Several hydrocarbon concentration anomalies are evident over both the Lisbon and Lightning Draw Southeast areas relative to background "water leg" areas (table 3). Alkane and aromatic hydrocarbon anomaly clusters are evident near cross-cutting faults in the south-central and northwestern parts of Lisbon field (figures 17 and 18). Hydrocarbon concentrations in surface soils over Lightning Draw Southeast field are most intense around and to the northwest of the Federal No. 1-31 well (for example, iso/normal-pentane, and toluene) and, in the case of toluene, along the trend of the anticline itself (figure 18). Benzene is mainly anomalous in the upper part of the Lisbon structure and northwest of the Federal No. 1-31 well in the Lightning Draw Southeast field (figure 19).

Although the hydrocarbon concentrations give some spatial indication of the fields, discriminant analysis was used to determine if there is a linear combination of variables that

Table 3. Organic and inorganic anomaly types identified in different sample media over Lisbon and Lightning Draw Southeast fields.

	Lisbon Field	**Lightning Draw Southeast Field**
Surface Soils	methane, ethane, ethene, propane, propene, i-butane, n-butane, butene, i-pentane, n-pentane, pentene, i-hexane, n-hexane, hexene, i-heptane, n-heptane, heptene, i-octane, n-octane, benzene, n-butylbenzene, cyclohexane, n-decane, n-dodecane, ethylbenzene, m-ethyltoluene, p-ethyltoluene, indane, naphthalene, n-nonane, n-propylbenzene, 1,2,4,5-tetramethylbenzene, toluene, 1,2,4-trimethylbenzene, 1,2,5-trimethylbenzene, n-undecane, m-xylene, p-xylene, and o-xylene Bi, Cd, Hg, Mo, Pb, U, V 297-305 nm factor scores, 395-470 nm factor scores	methane, ethane, ethene, propane, propene, i-butane, n-butane, butene, i-pentane, n-pentane, pentene, i-hexane, n-hexane, hexene, i-heptane, n-octane, benzene, n-butylbenzene, n-decane, n-dodecane, ethylbenzene, m-ethyltoluene, p-ethyltoluene, indane, naphthalene, n-nonane, n-propylbenzene, 1,2,4,5-tetramethylbenzene, toluene, 1,2,4-trimethylbenzene, 1,3,5-trimethylbenzene, n-undecane, m-xylene, p-xylene, and o-xylene Ag, Al, As, Be, Bi, Co, Cu, Ga, Hf, Hg, La, Li, Mo, Pb, Sc, Sn, Sr, Tl, U, V, Zn, Zr 297-305 nm factor scores, 395-470 nm factor scores
Outcrop Lichen	ethane, ethene, propene, i-butane, butene, pentene, hexene, benzene, n-butylbenzene, n-decane, ethylbenzene, m-ethyltoluene, p-ethyltoluene, indane, naphthalene, n-nonane, n-propylbenzene, 1,2,4,5-tetramethylbenzene, toluene, 1,2,4-trimethylbenzene, 1,2,5-trimethylbenzene, m-xylene, p-xylene, and o-xylene Ag, Al, As, Au, B, Ba, Bi, Co, Cu, Ga, Hf, K, La, Li, Mo, Na, Pb, Re, Sb, Sc, Sn, Sr, Th, Ti, Tl, U, V, Y, Zn, Zr 305 nm Intensity	methane, ethane, ethene, propene, i-butane, butene, pentene, hexene, benzene, indane, naphthalene, 1,2,4-trimethylbenzene, 1,2,5-trimethylbenzene, o-xylene. Ag, Al, As, B, Ba, Bi, Co, Cu, Ga, Hf, K, Li, Mo, Na, Pb, Sb, Sc, Sr, Th, Tl, Zr 305 nm Intensity
Outcrop Soils	methane, ethane, propane, propene, butene, pentene, hexene, n-octane, n-butylbenzene, m-ethyltoluene, p-ethyltoluene, naphthalene, 1,2,4,5-tetramethylbenzene, 1,2,4-trimethylbenzene, 1,2,5-trimethylbenzene, n-undecane, n-dodecane Ag, Cl, Na, NO_4, Re, S, Se, SO_4, U, Y 305 and 335 nm Intensity	methane, ethane, ethene, propane, propene, butene, pentene, hexene, n-octane, ethylbenzene, n-butylbenzene, m-ethyltoluene, p-ethyltoluene, indane, naphthalene, 1,2,4,5-tetramethylbenzene, 1,2,4-trimethylbenzene, 1,2,5-trimethylbenzene, n-undecane, m-xylene, p-xylene, Ag, As, Co, S, Se, Y
Free Gas	No free gas collected	ethane, propane, propene, i-butane, n-butane, i-pentane, n-pentane, i-hexane, hydrogen, carbon dioxide

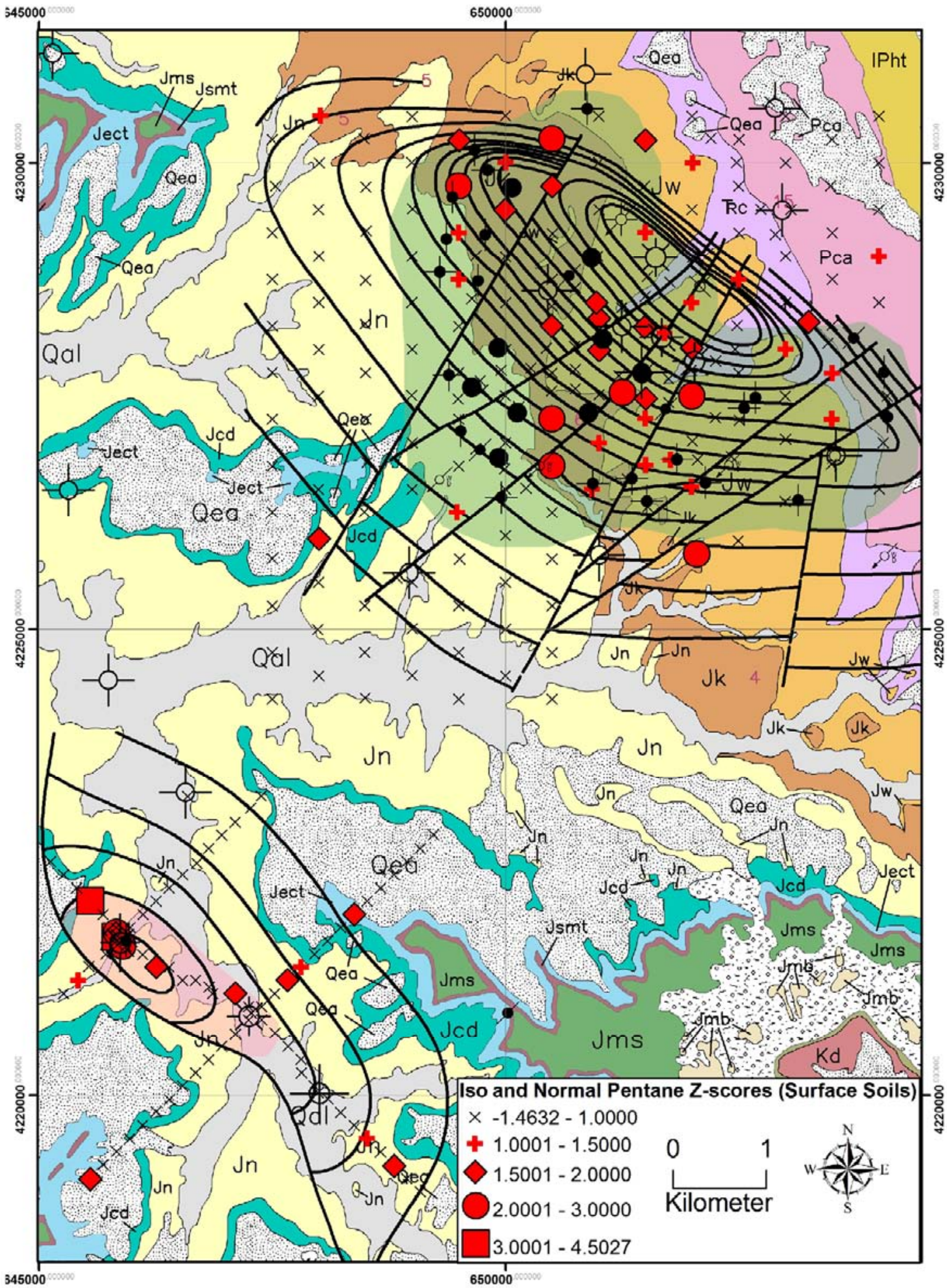


Figure 17. Distribution of iso- and normal-pentane Z-scores in surface soils over the Lisbon and Lightning Draw Southeast fields. Surface geology modified from Doelling (2005); see figure 10 for explanation of geologic units. Form line contours based on top of structure of the Leadville Limestone shown on figures 8 and 9; Lisbon and Lightning Draw southeast fields shown in bluish green and pink, respectively.

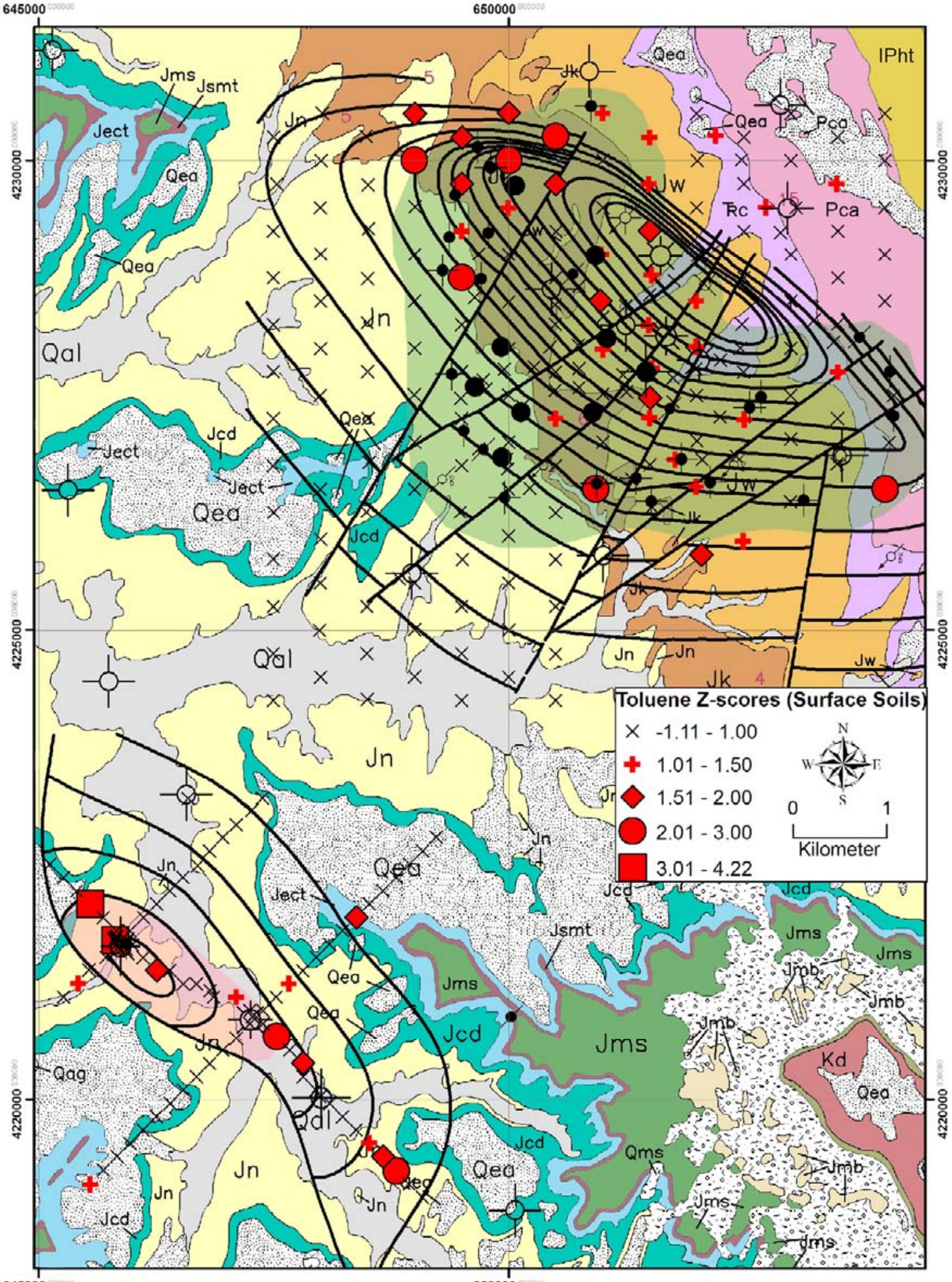


Figure 18. Distribution of toluene Z-scores in surface soils over the Lisbon and Lightning Draw Southeast fields. Surface geology modified from Doelling (2005); see figures 8 and 10 for explanations of well symbols and geologic units. Form line contours based on top of structure of the Leadville Limestone shown on figures 8 and 9; Lisbon and Lightning Draw southeast fields shown in bluish green and pink, respectively.

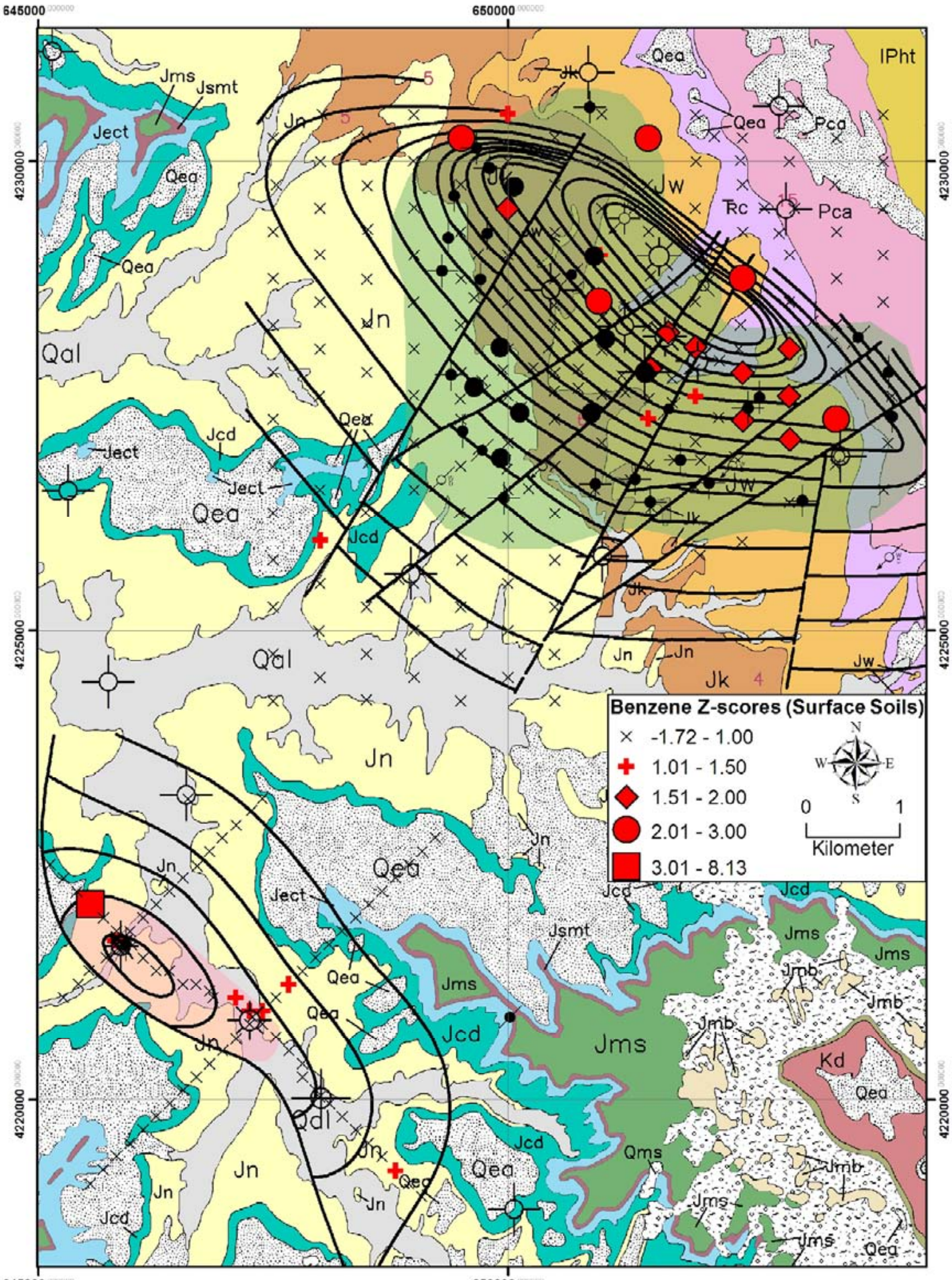


Figure 19. Distribution of benzene Z-scores in surface soils over the Lisbon and Lightning Draw Southeast fields. Surface geology modified from Doelling (2005); see figures 8 and 10 for explanations of well symbols and geologic units. Form line contours based on top of structure of the Leadville Limestone shown on figures 8 and 9; Lisbon and Lightning Draw southeast fields shown in bluish green and pink, respectively.

better distinguishes microseepage over the fields from that over the water legs. If there is such a combination of variables, then it is important to determine which variables have the most discriminating power.

Surface Soils (C_1 to C_{12} Data)

The first discriminant analysis model attempts to distinguish hydrocarbon microseepage between the gas cap (Lisbon No. D-810 well), oil leg (Lisbon No. C-99 well), and water leg at Lisbon field (figure 20). In this model, the microseepage over the gas cap is distinguished from that over the water leg and iso/normal pentane, benzene, and propane are the most important variables for this discrimination (figure 21). Soils around the very productive Lisbon No. C-910 gas well are predicted as gas prone, and the model is therefore robust. Soil samples that fall into the "gas cap" category cluster mainly in the "up-structure" part of the field where most of the gas production comes from. Two samples over the top of the Lightning Draw Southeast structure also have "gas cap" type compositional character. The microseepage character of the less productive oil leg shows less distinct separation from the water leg than the gas cap does (figure 21). Toluene contributes most to the discrimination of microseepage between the oil and water legs. Samples around the Lisbon No. D-716, Federal No. 1-31, and Evelyn Chambers Government No. 1 wells are oil prone in character (figure 22).

The second discriminant analysis model tests for differences in microseepage between productive "gas/oil" parts of the Lisbon field and the water leg (figure 23). Samples around productive wells in the Lightning Draw Southeast field are also compared with the water leg samples. Samples with Lisbon gas/oil microseepage character again plot mainly in the upper productive part of the anticline and, in this case, more samples over and down-structure of Lightning Draw Southeast are classified as Lisbon gas/oil prone (figure 24). Ethane and normal butane are important variables for discriminating between the productive part of Lisbon and the its non-productive water-leg part. The microseepage over the productive part of the Lightning Draw Southeast field is distinct from that over the Lisbon water leg, and ethane and normal butane again are the most influential discriminating variables (figure 25). Ethylene, methane, iso/normal pentane, and propane are also important variables for discrimination. Several samples along the Lightning Draw Southeast anticline are gas prone in character as well as two samples downdip of the crest of the anticline. Samples in the upper part of the Lisbon oil leg also fall into the Lightning Draw Southeast productive gas category (figure 25).

Outcrop Fracture-Fill Lichen and Soils (C_1 to C_{12} Data)

Several hydrocarbons are anomalous in outcrop fracture-fill lichen and soils over Lisbon and Lightning Draw Southeast fields as opposed to the Lisbon water leg (table 3). Discriminant analysis was performed on thermally desorbed C_1 to C_{12} data from outcrop lichen to determine if the microseepage over Lisbon and Lightning Southeast Draw is compositionally distinct from that over the Lisbon water leg and, if so, to identify which variables contribute most to the discrimination. Outcrop lichen samples over the gas cap, oil leg, and water leg at Lisbon were first analyzed for compositional differences in a three-component model, and then samples over Lightning Draw Southeast were compared with those over the Lisbon water leg (figure 26). Lichen samples over the Lisbon gas cap, oil leg, and water leg are clearly different in terms of their compositional character as shown on the canonical score plot in figure 27. Methane

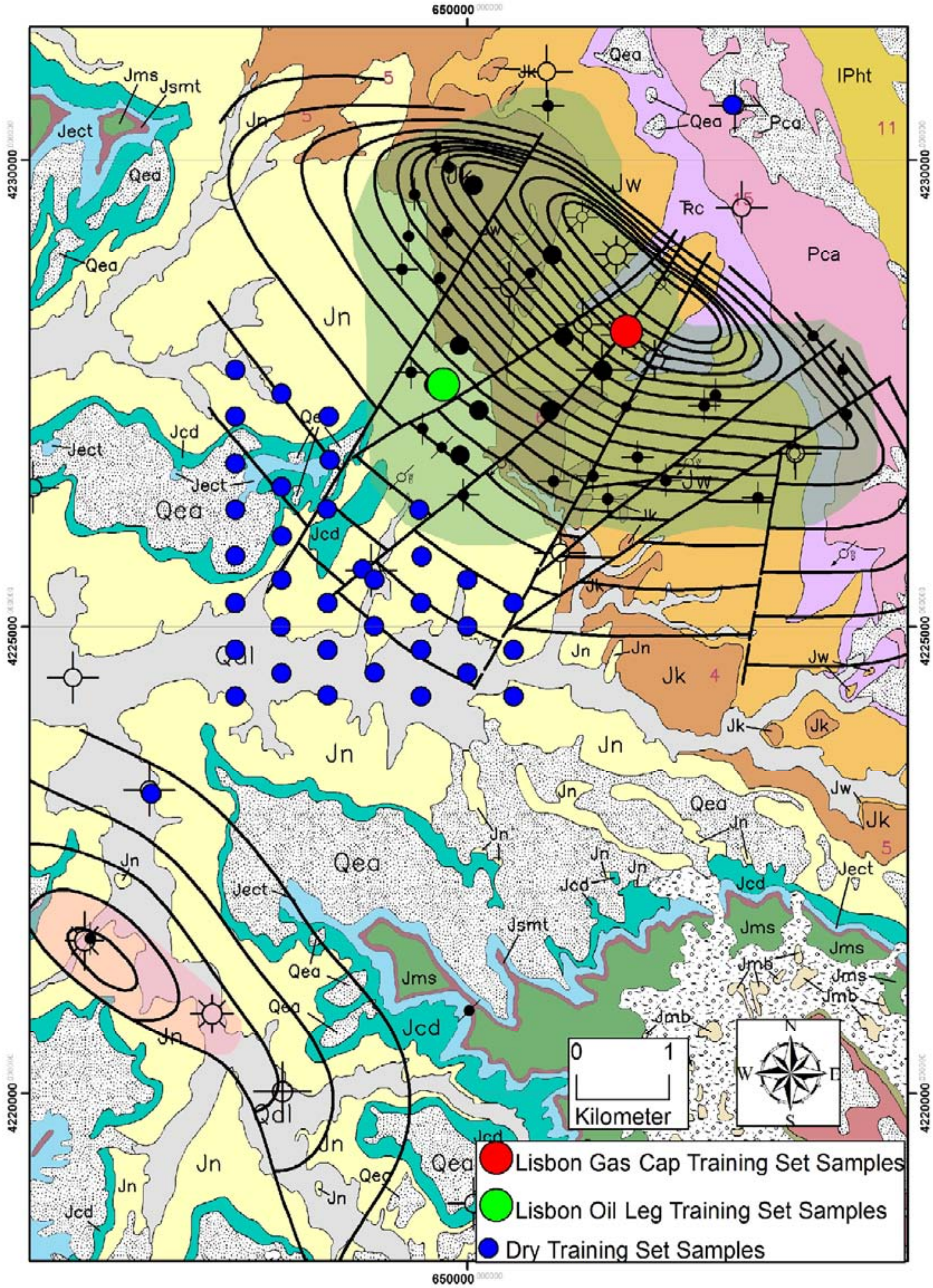
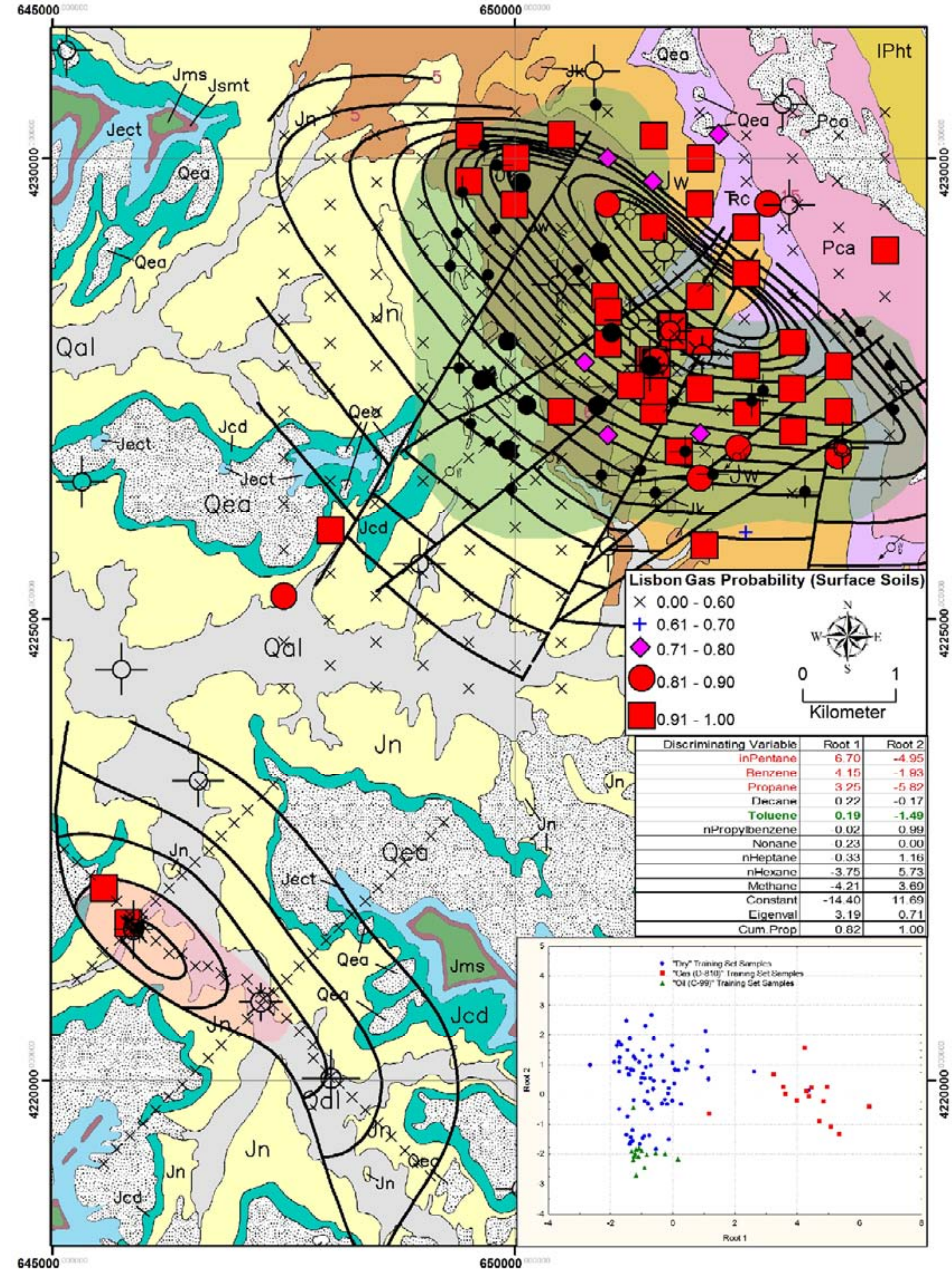


Figure 20. Surface soil training set samples used for three-component Lisbon gas cap versus oil leg versus water leg discriminant analysis model. Surface geology modified from Doelling (2005); see figures 8 and 10 for explanations of well symbols and geologic units. Form line contours based on top of structure of the Leadville Limestone shown on figures 8 and 9; Lisbon and Lightning Draw southeast fields shown in bluish green and pink, respectively.



Discriminating Variable	Root 1	Root 2
inPentane	6.70	-4.95
Benzene	4.15	-1.93
Propane	3.25	-5.82
Decane	0.22	-0.17
Toluene	0.19	-1.49
nPropylbenzene	0.02	0.99
Nonane	0.23	0.00
nHeptane	0.33	1.16
nHexane	-3.75	5.73
Methane	-4.21	3.69
Constant	-14.40	11.69
Eigenval	3.19	0.71
Cum.Prop	0.82	1.00

Figure 21. Distribution of Lisbon gas probabilities derived from three-component discriminant analysis of thermally desorbed C_1 to C_{12} hydrocarbon from surface soils. Surface geology modified from Doelling (2005); see figures 8 and 10 for explanations of well symbols and geologic units. Form line contours based on top of structure of the Leadville Limestone shown on figures 8 and 9; Lisbon and Lightning Draw southeast fields shown in bluish green and pink, respectively.

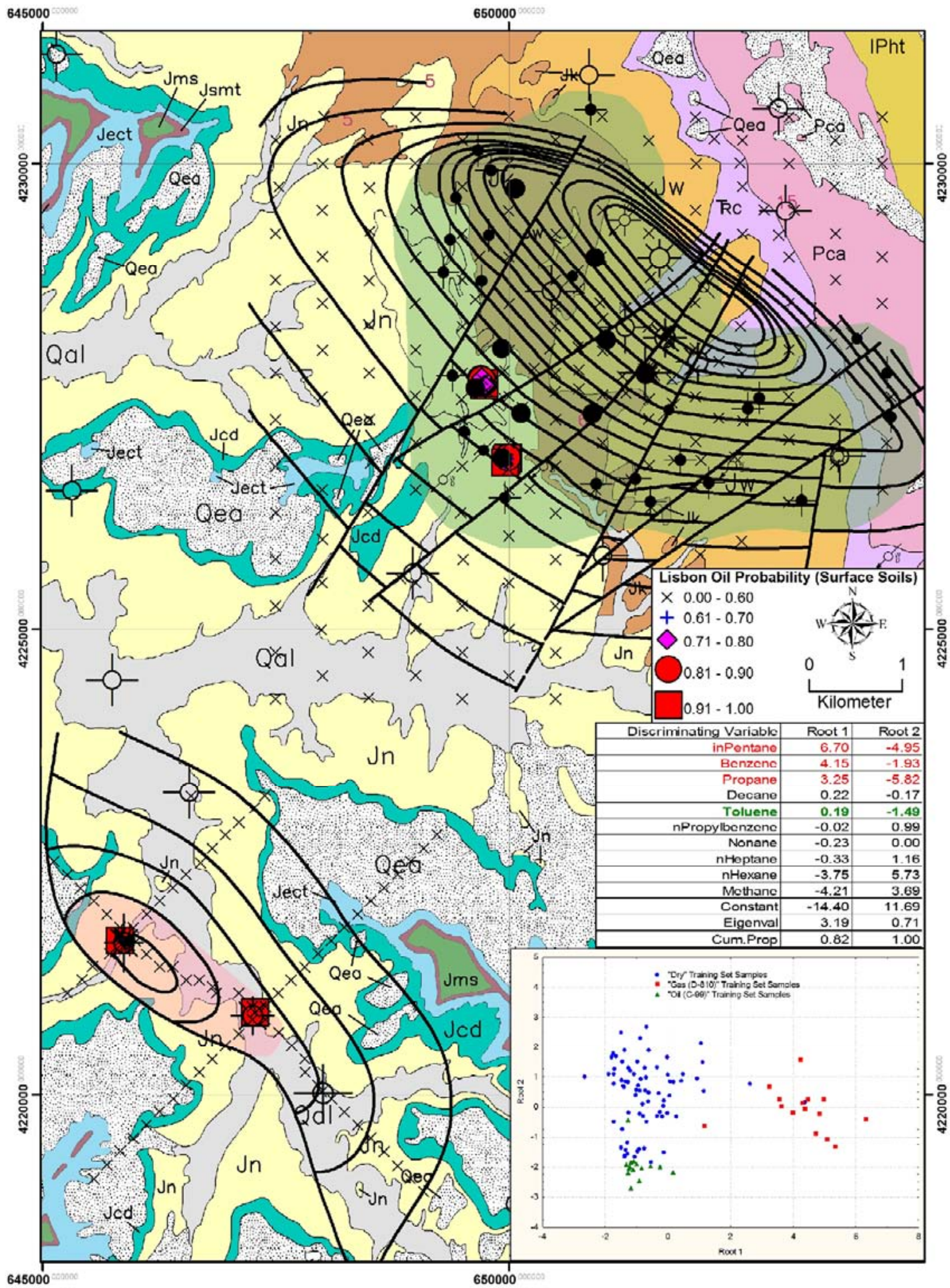


Figure 22. Distribution of Lisbon oil probabilities derived from three-component discriminant analysis of thermally desorbed C_1 to C_{12} hydrocarbon from surface soils. Surface geology modified from Doelling (2005); see figures 8 and 10 for explanations of well symbols and geologic units. Form line contours based on top of structure of the Leadville Limestone shown on figures 8 and 9; Lisbon and Lightning Draw southeast fields shown in bluish green and pink, respectively.

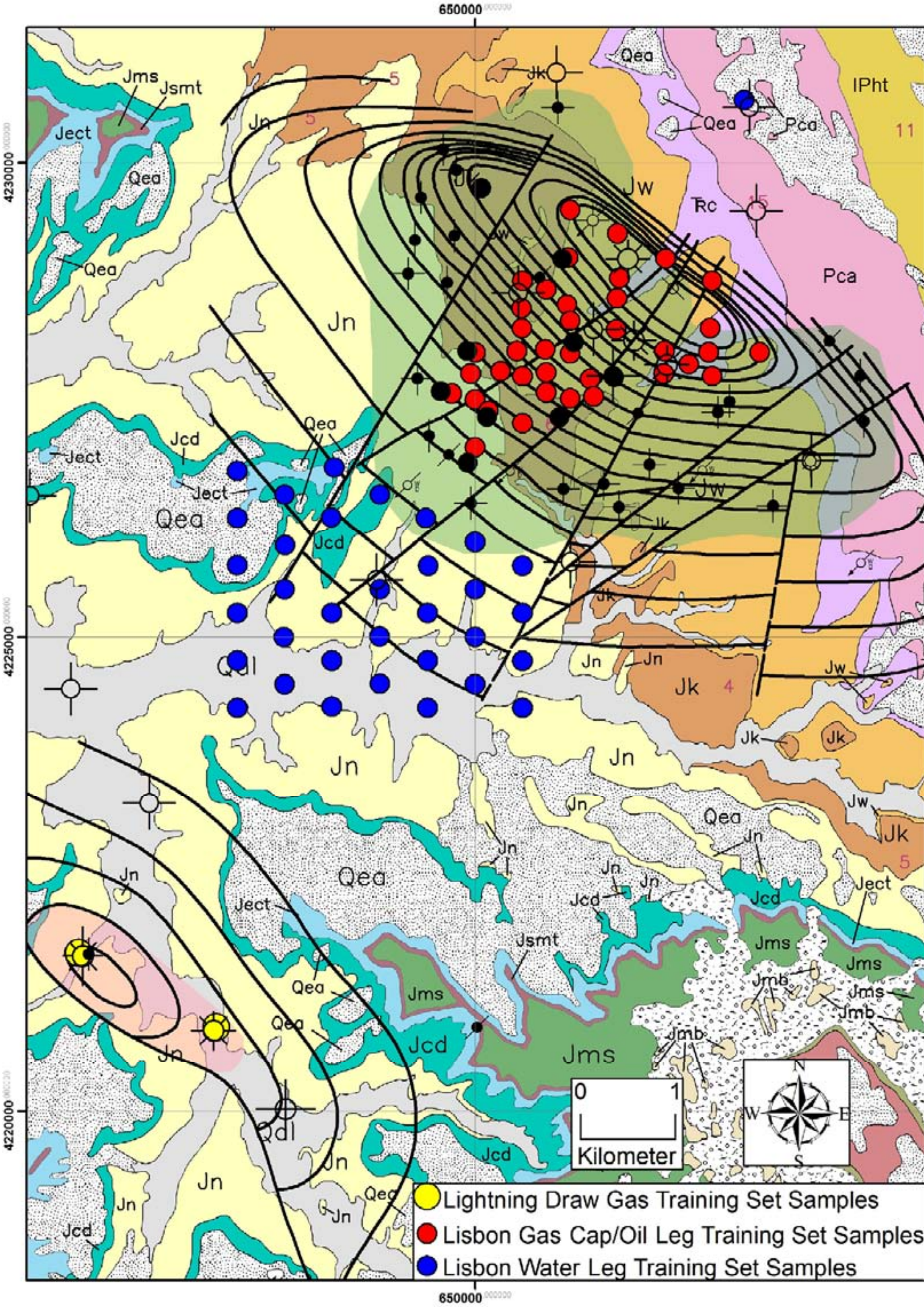


Figure 23. Surface soil training set samples used for two component Lisbon gas cap/oil leg versus water leg and Lightning Draw Southeast gas versus Lisbon water leg discriminant analysis models. Surface geology modified from Doelling (2005); see figures 8 and 10 for explanations of well symbols and geologic units. Form line contours based on top of structure of the Leadville Limestone shown on figures 8 and 9; Lisbon and Lightning Draw southeast fields shown in bluish green and pink, respectively.

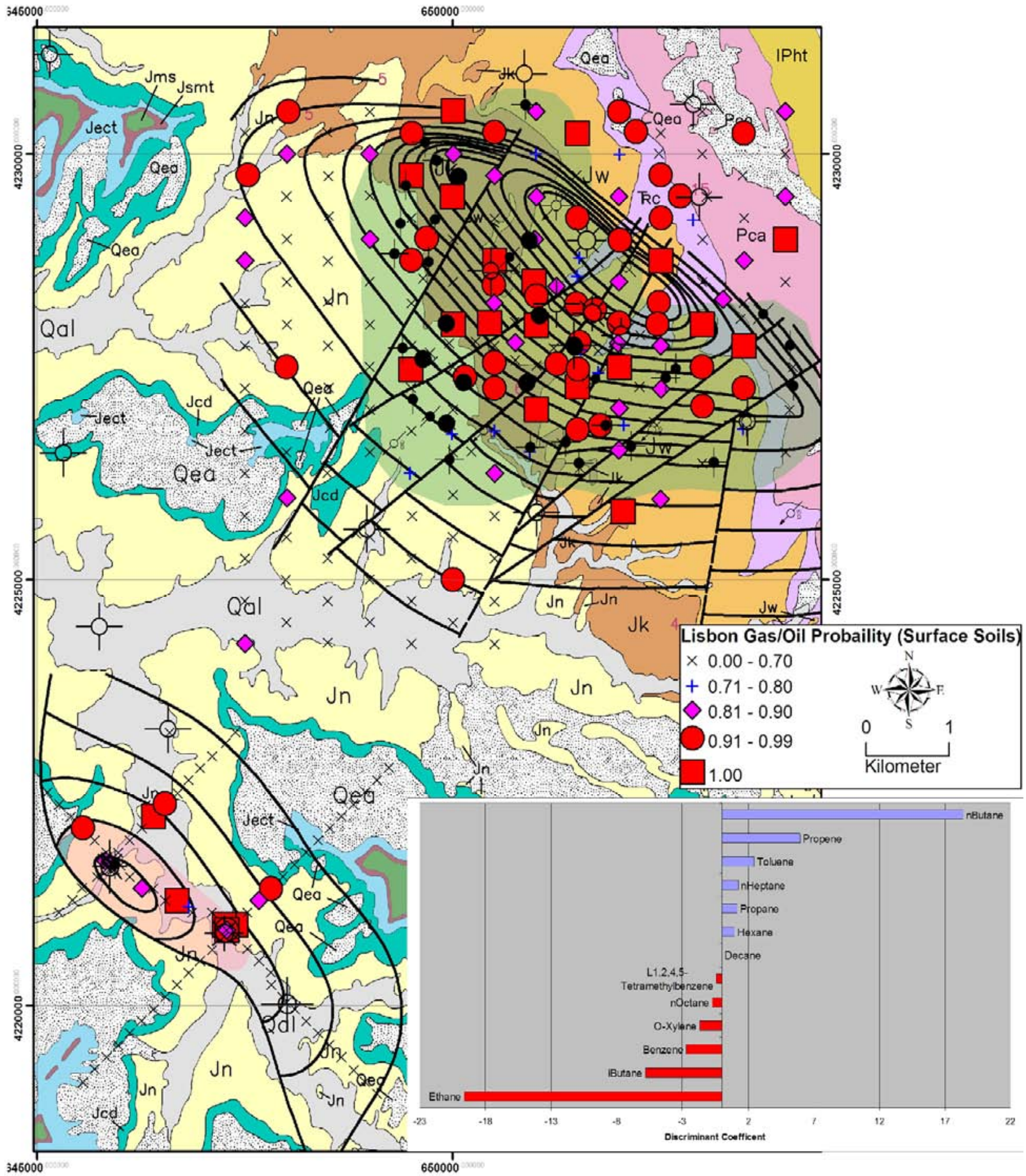


Figure 24. Distribution of Lisbon gas-oil probabilities derived from two-component discriminant analysis of thermally desorbed C_1 to C_{12} hydrocarbon from surface soils. Surface geology modified from Doelling (2005); see figures 8 and 10 for explanations of well symbols and geologic units. Form line contours based on top of structure of the Leadville Limestone shown on figures 8 and 9; Lisbon and Lightning Draw southeast fields shown in bluish green and pink, respectively.

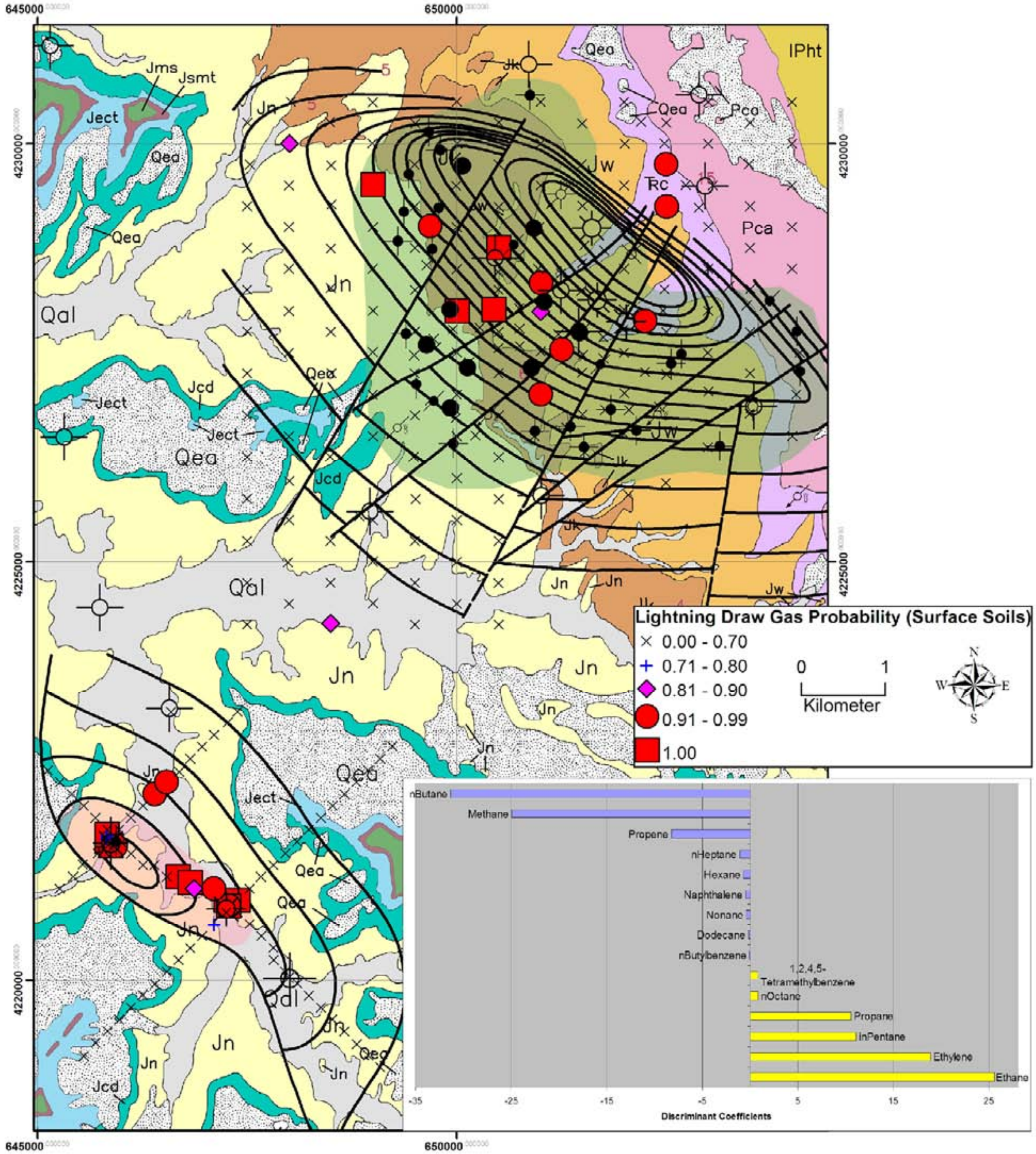


Figure 25. Distribution of Lightning Draw Southeast gas probabilities derived from three-component discriminant analysis of thermally desorbed C_1 to C_{12} hydrocarbon from surface soils. Surface geology modified from Doelling (2005); see figures 8 and 10 for explanations of well symbols and geologic units. Form line contours based on top of structure of the Leadville Limestone shown on figures 8 and 9; Lisbon and Lightning Draw southeast fields shown in bluish green and pink, respectively.

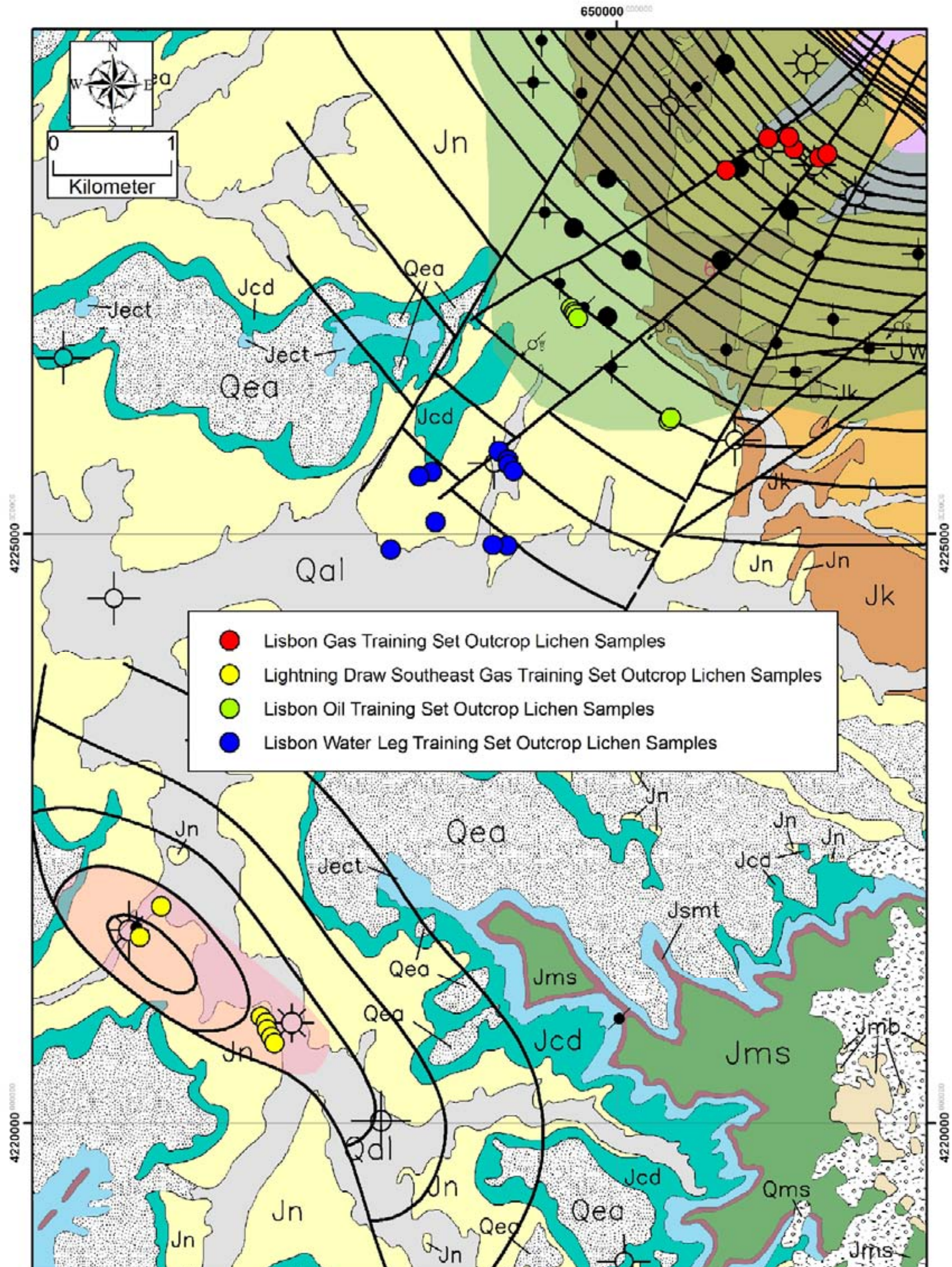


Figure 26. Outcrop lichen training set samples used for three-component Lisbon gas cap versus oil leg versus water leg and two-component Lightning Draw Southeast gas versus Lisbon water leg discriminant analysis models. Surface geology modified from Doelling (2005); see figures 8 and 10 for explanations of well symbols and geologic units. Form line contours based on top of structure of the Leadville Limestone shown on figures 8 and 9; Lisbon and Lightning Draw southeast fields shown in bluish green and pink, respectively.

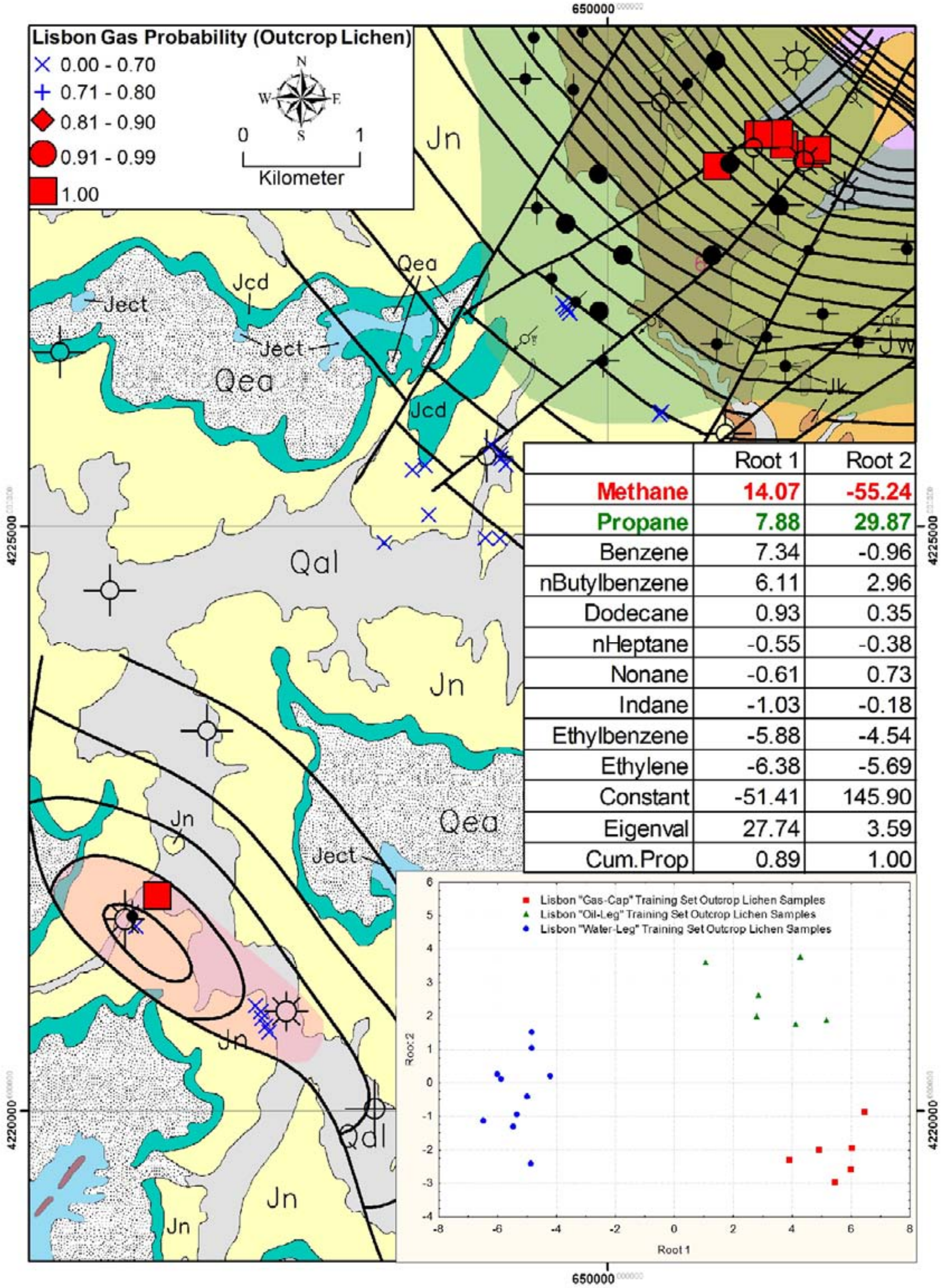


***Figure 27.** Distribution of Lisbon gas probability derived from three-component discriminant analysis of thermally desorbed C_1 to C_{12} hydrocarbon from outcrop lichen samples. Surface geology modified from Doelling (2005); see figures 8 and 10 for explanations of well symbols and geologic units. Form line contours based on top of structure of the Leadville Limestone shown on figures 8 and 9; Lisbon and Lightning Draw southeast fields shown in bluish green and pink, respectively.*

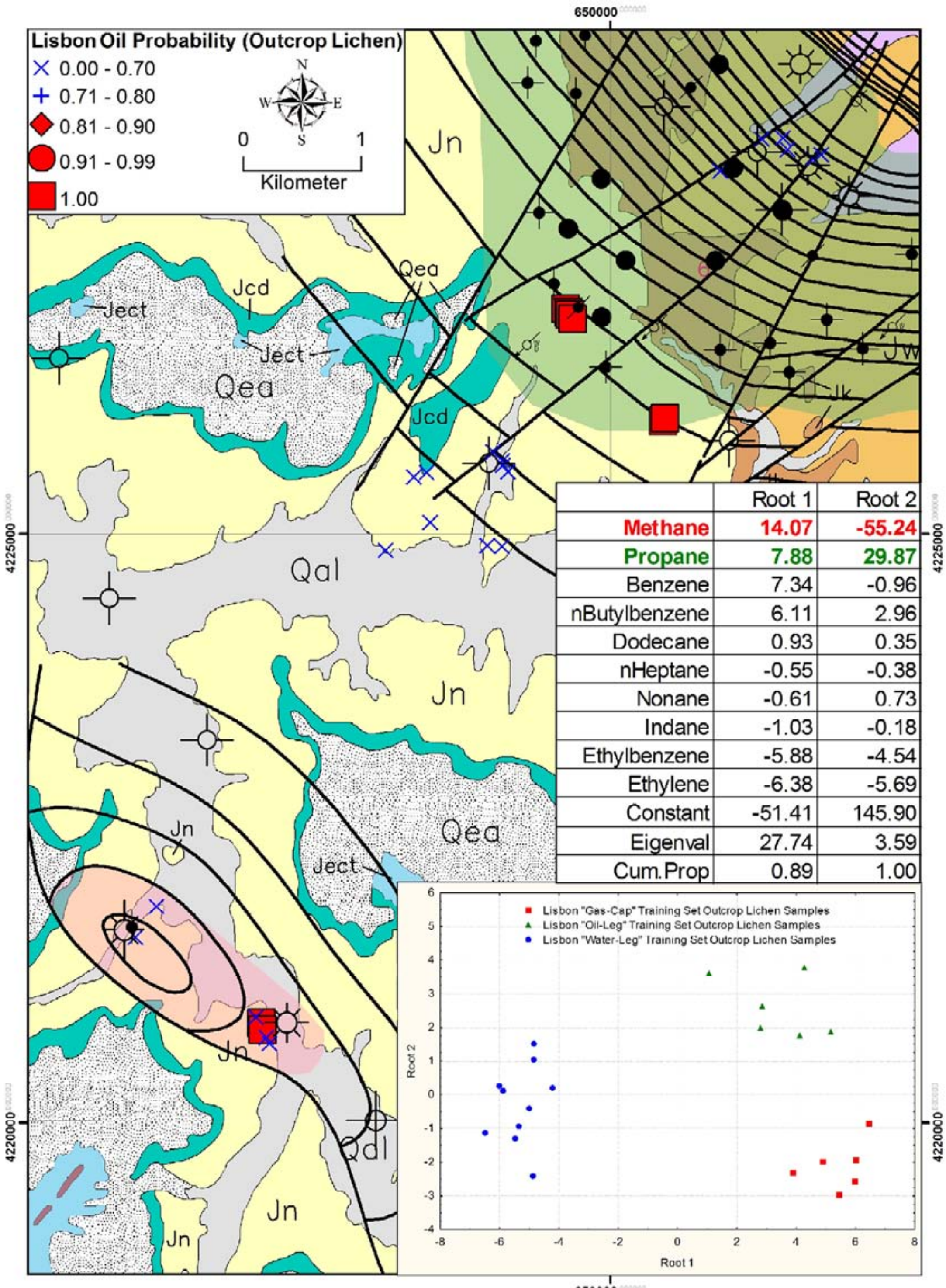
contributes most to the discrimination of the gas cap from the oil- and water legs, and propane is the most important variable for separating the oil leg from the gas cap and water leg (figure 27). One of the seven lichen samples (14%) over the Lightning Draw Southeast field near Federal No. 1-31 well is classified into the productive Lisbon gas cap category (figure 27). Two of seven (29%) lichen samples over Lightning Draw Southeast near the Evelyn Chambers Government No. 1 well are oil prone in character (figure 28). When the lichen samples over Lightning Draw Southeast gas field are compared with those over the Lisbon water leg, nine of twelve (75%) samples are gas prone in character (figure 29). Important variables that contribute to the distinction between samples over Lightning Draw Southeast and the Lisbon water leg are ethane, normal hexane, propane, ethylene, normal butylbenzene, and ethylbenzene.

The same discriminant models were tested on C_1 to C_{12} data from outcrop fracture-fill soils collected over the Lisbon gas cap, oil leg, and water leg, and Lightning Draw Southeast field (figure 30). The compositional character of outcrop-soil microseepage from outcrop soil samples of the Lisbon gas cap, oil leg, and water leg is even more distinct than that shown by the lichen training set samples (figure 31). As in the outcrop lichen samples, variables in outcrop samples that contribute most to the discrimination of the gas cap and oil leg are methane and propane, respectively. A higher percentage of the outcrop soils over the Lightning Draw Southeast field (71%) exhibit a Lisbon gas-prone character as compared with only 14% of the lichen samples. None of the outcrop soils over Lightning Draw Southeast fall into the Lisbon oil-leg category (figure 32). Outcrop soil-gas samples from Lightning Draw Southeast are compositionally distinct from those over the Lisbon water leg. Only 31% of the Lisbon field outcrop soil samples match the character of the Lightning Draw Southeast gas-prone samples (figure 33) compared with 75% of the lichen samples from Lisbon field (figure 29). Variables that significantly contribute to the discrimination of microseepage in outcrop soils over Lightning Draw Southeast and the Lisbon water leg are iso/normal-pentane, normal-butane, and ethylbenzene.

Surface Soils (Synchronous Scanned Fluorescence Data)

Figure 34 depicts the synchronous scanned fluorescence patterns for high, medium, and low gravity oils. In comparison with these spectra, the Lisbon oil samples (oils from the Lisbon Nos. C-99 and D-716 wells) have condensate to medium gravity patterns, and they can therefore be classified as "light oils" (figures 35a and 35b). Background and anomalous fluorescence patterns are clearly distinguished in surface soils. In background areas, peak wavelengths are low intensity and below the 300 nm wavelength (figure 35c). Spectra in anomalous areas are more intense and extend to longer wavelengths (figures 35d and 35e). Soil samples with these anomalous spectra contain light oil that has been weathered through chemical and biological oxidation processes. As weathering progresses, the once-fresh light oil (as in figures 35a and 35b) gradually loses its light, single- and double-ring aromatic compounds leaving a residue of 3- to 6-ring aromatics that fluoresce in the 395 to 470 nm range (figures 35d and 35e). Asphalt dust from nearby paved roads can add intensity to peaks in the 350 to 450 nm range thereby producing false anomalies (figure 35f). Soil samples collected near paved roads in this study were therefore removed from the database prior to interpreting the synchronous scanned fluorescence data.

Two main fluorescence intensity associations are evident from factor analysis of the



	Root 1	Root 2
Methane	14.07	-55.24
Propane	7.88	29.87
Benzene	7.34	-0.96
nButylbenzene	6.11	2.96
Dodecane	0.93	0.35
nHeptane	-0.55	-0.38
Nonane	-0.61	0.73
Indane	-1.03	-0.18
Ethylbenzene	-5.88	-4.54
Ethylene	-6.38	-5.69
Constant	-51.41	145.90
Eigenval	27.74	3.59
Cum.Prop	0.89	1.00

Figure 28. Distribution of Lisbon oil probability derived from three-component discriminant analysis of thermally desorbed C_1 to C_{12} hydrocarbon from outcrop lichen samples. Surface geology modified from Doelling (2005); see figures 8 and 10 for explanations of well symbols and geologic units. Form line contours based on top of structure of the Leadville Limestone shown on figures 8 and 9; Lisbon and Lightning Draw southeast fields shown in bluish green and pink, respectively.

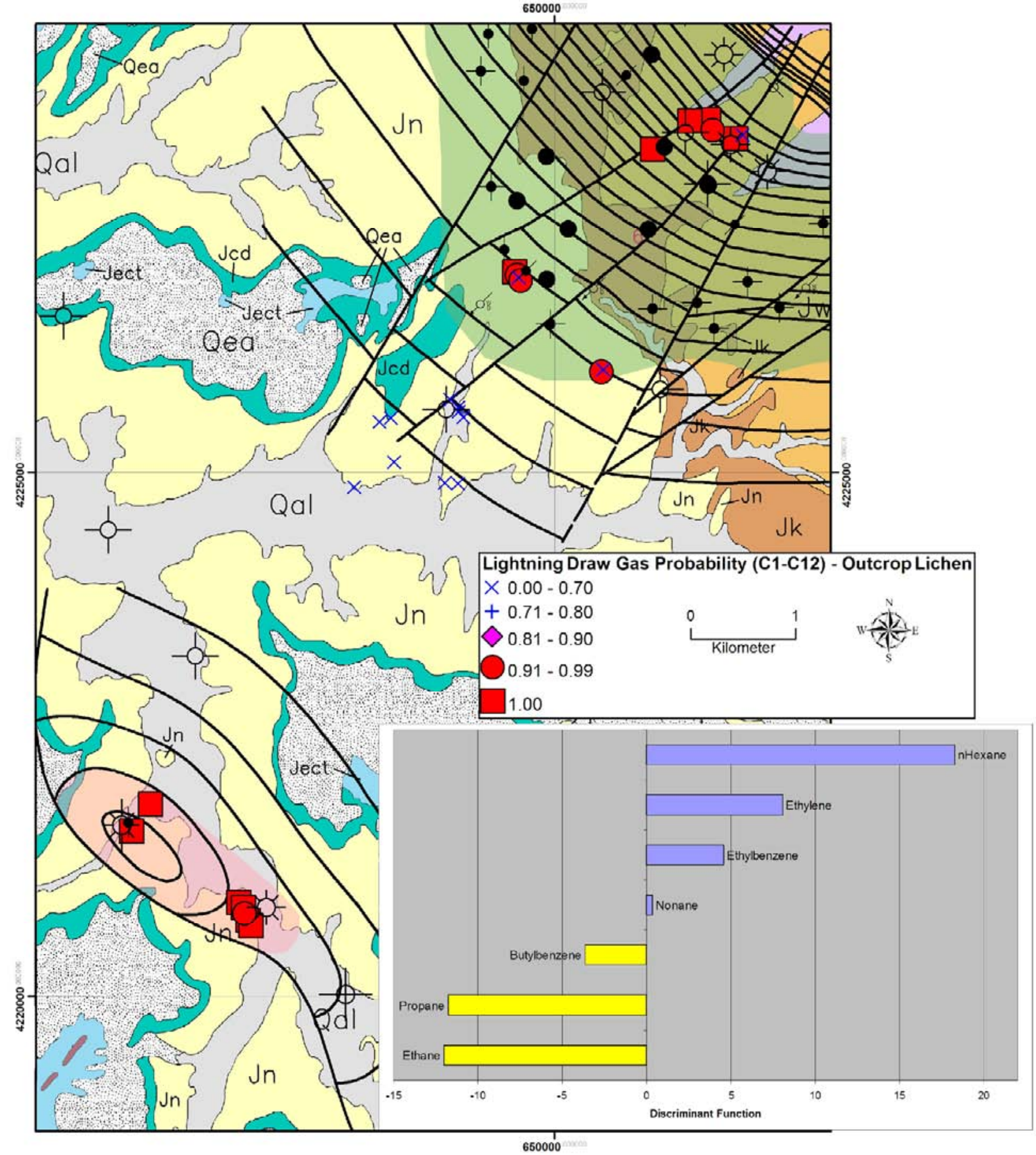


Figure 29. Distribution of Lightning Draw Southeast gas probabilities derived from two-component discriminant analysis of thermally desorbed C_1 to C_{12} hydrocarbon from outcrop lichen samples. Surface geology modified from Doelling (2005); see figures 8 and 10 for explanations of well symbols and geologic units. Form line contours based on top of structure of the Leadville Limestone shown on figures 8 and 9; Lisbon and Lightning Draw southeast fields shown in bluish green and pink, respectively.

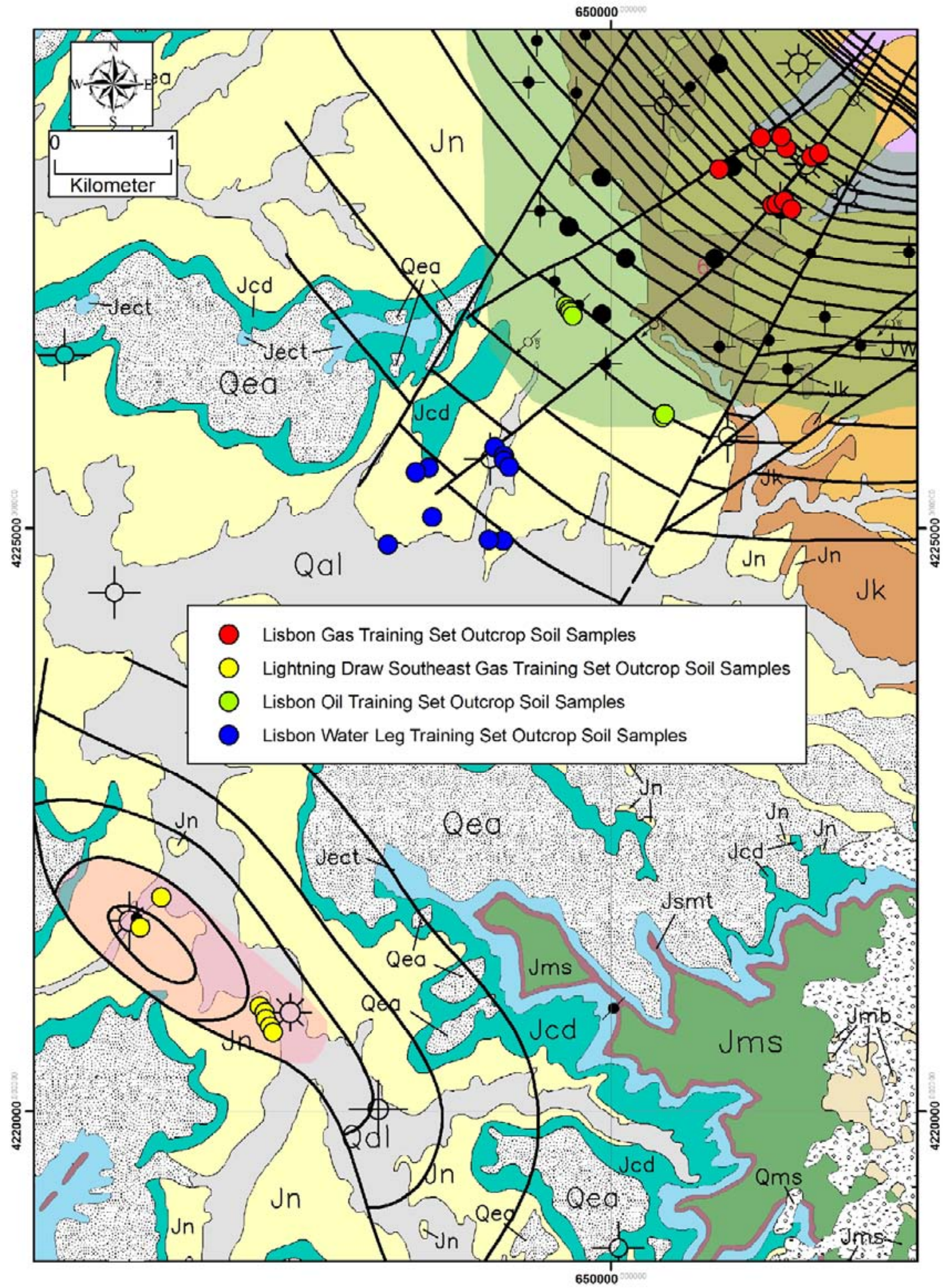
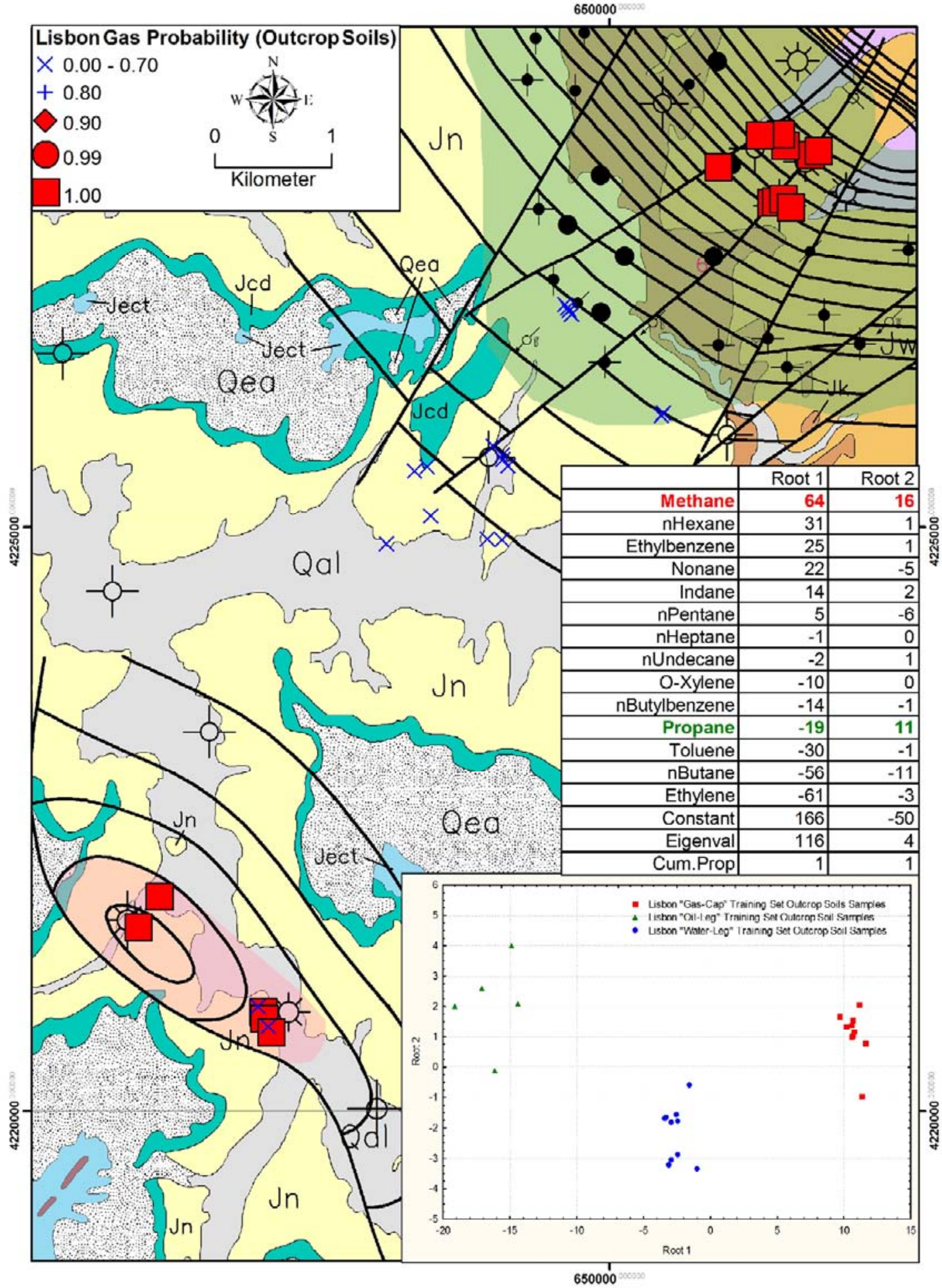
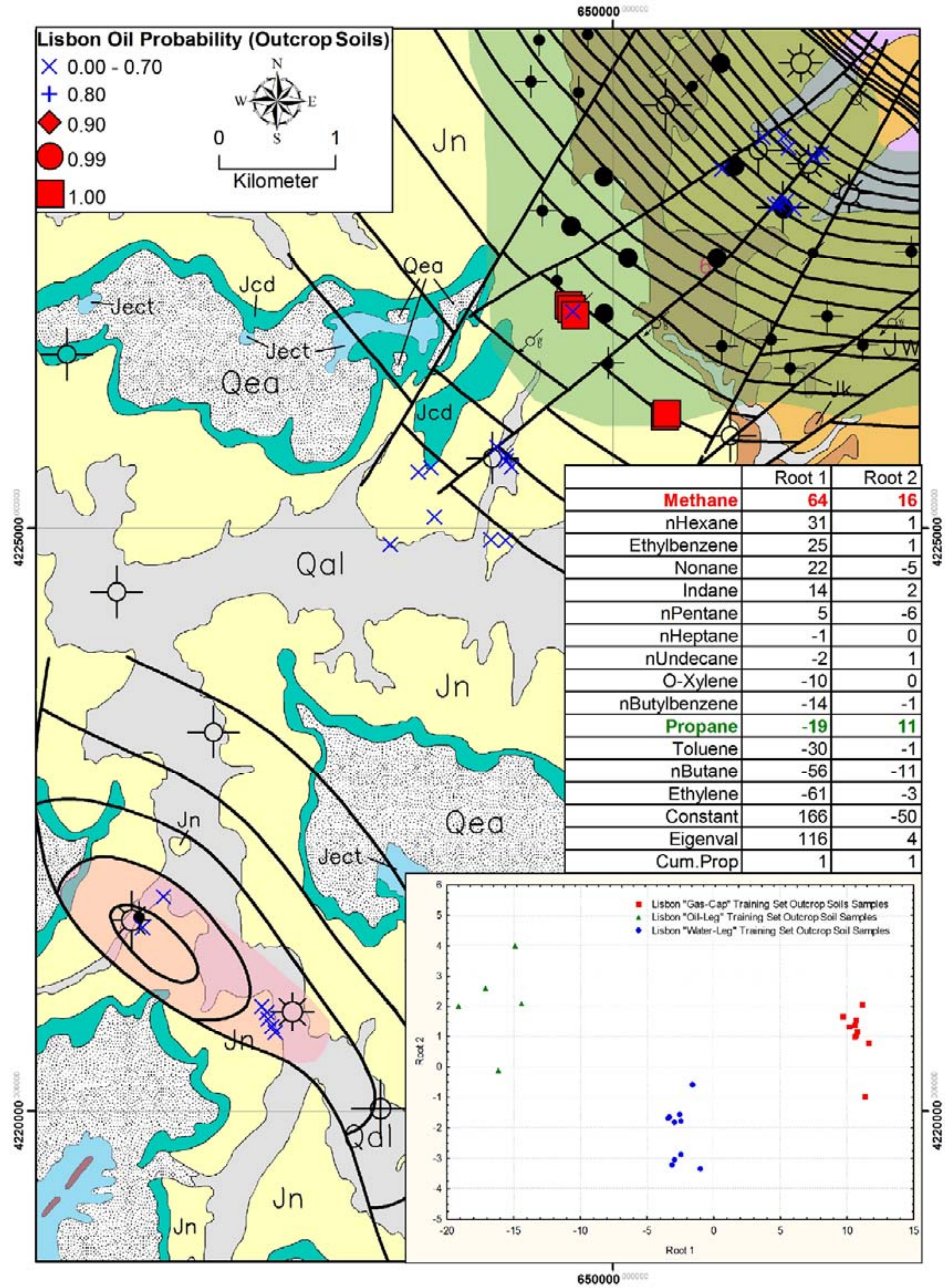


Figure 30. Outcrop soil training set samples used for three-component Lisbon gas cap versus oil leg versus water leg and two-component Lightning Draw Southeast gas versus Lisbon water leg discriminant analysis models. Surface geology modified from Doelling (2005); see figures 8 and 10 for explanations of well symbols and geologic units. Form line contours based on top of structure of the Leadville Limestone shown on figures 8 and 9; Lisbon and Lightning Draw southeast fields shown in bluish green and pink, respectively.



	Root 1	Root 2
Methane	64	16
nHexane	31	1
Ethylbenzene	25	1
Nonane	22	-5
Indane	14	2
nPentane	5	-6
nHeptane	-1	0
nUndecane	-2	1
O-Xylene	-10	0
nButylbenzene	-14	-1
Propane	-19	11
Toluene	-30	-1
nButane	-56	-11
Ethylene	-61	-3
Constant	166	-50
Eigenval	116	4
Cum.Prop	1	1

***Figure 31.** Distribution of Lisbon gas probability derived from three-component discriminant analysis of thermally desorbed C_1 to C_{12} hydrocarbon from outcrop soil samples. Surface geology modified from Doelling (2005); see figures 8 and 10 for explanations of well symbols and geologic units. Form line contours based on top of structure of the Leadville Limestone shown on figures 8 and 9; Lisbon and Lightning Draw southeast fields shown in bluish green and pink, respectively.*



	Root 1	Root 2
Methane	64	16
nHexane	31	1
Ethylbenzene	25	1
Nonane	22	-5
Indane	14	2
nPentane	5	-6
nHeptane	-1	0
nUndecane	-2	1
O-Xylene	-10	0
nButylbenzene	-14	-1
Propane	-19	11
Toluene	-30	-1
nButane	-56	-11
Ethylene	-61	-3
Constant	166	-50
Eigenval	116	4
Cum.Prop	1	1

***Figure 32.** Distribution of Lisbon oil probability derived from three-component discriminant analysis of thermally desorbed C_1 to C_{12} hydrocarbon from outcrop soil samples. Surface geology modified from Doelling (2005); see figures 8 and 10 for explanations of well symbols and geologic units. Form line contours based on top of structure of the Leadville Limestone shown on figures 8 and 9; Lisbon and Lightning Draw southeast fields shown in bluish green and pink, respectively.*

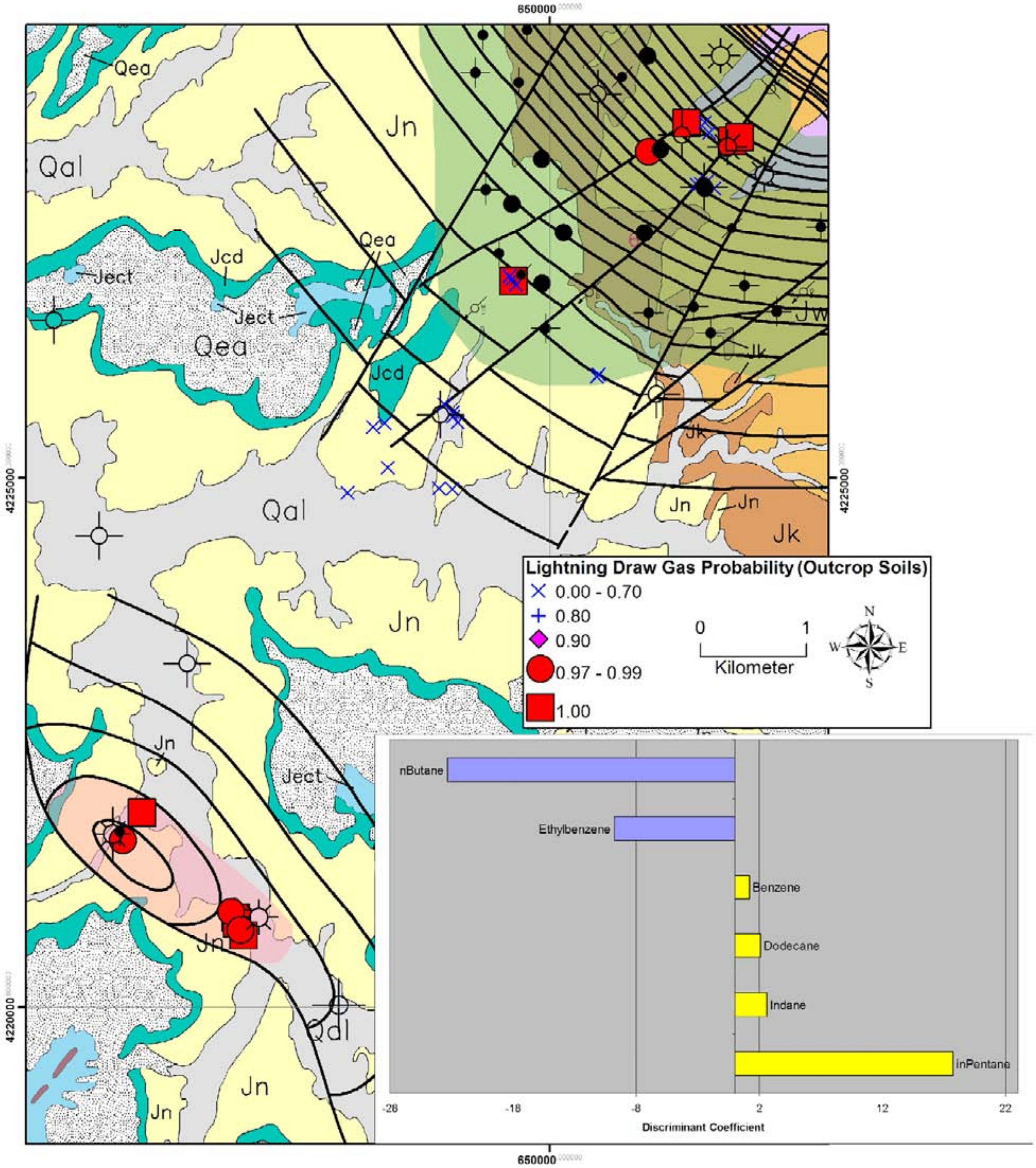


Figure 33. Distribution of Lightning Draw Southeast gas probabilities derived from two-component discriminant analysis of thermally desorbed C_1 to C_{12} hydrocarbon from outcrop soil samples. Surface geology modified from Doelling (2005); see figures 8 and 10 for explanations of well symbols and geologic units. Form line contours based on top of structure of the Leadville Limestone shown on figures 8 and 9; Lisbon and Lightning Draw southeast fields shown in bluish green and pink, respectively.

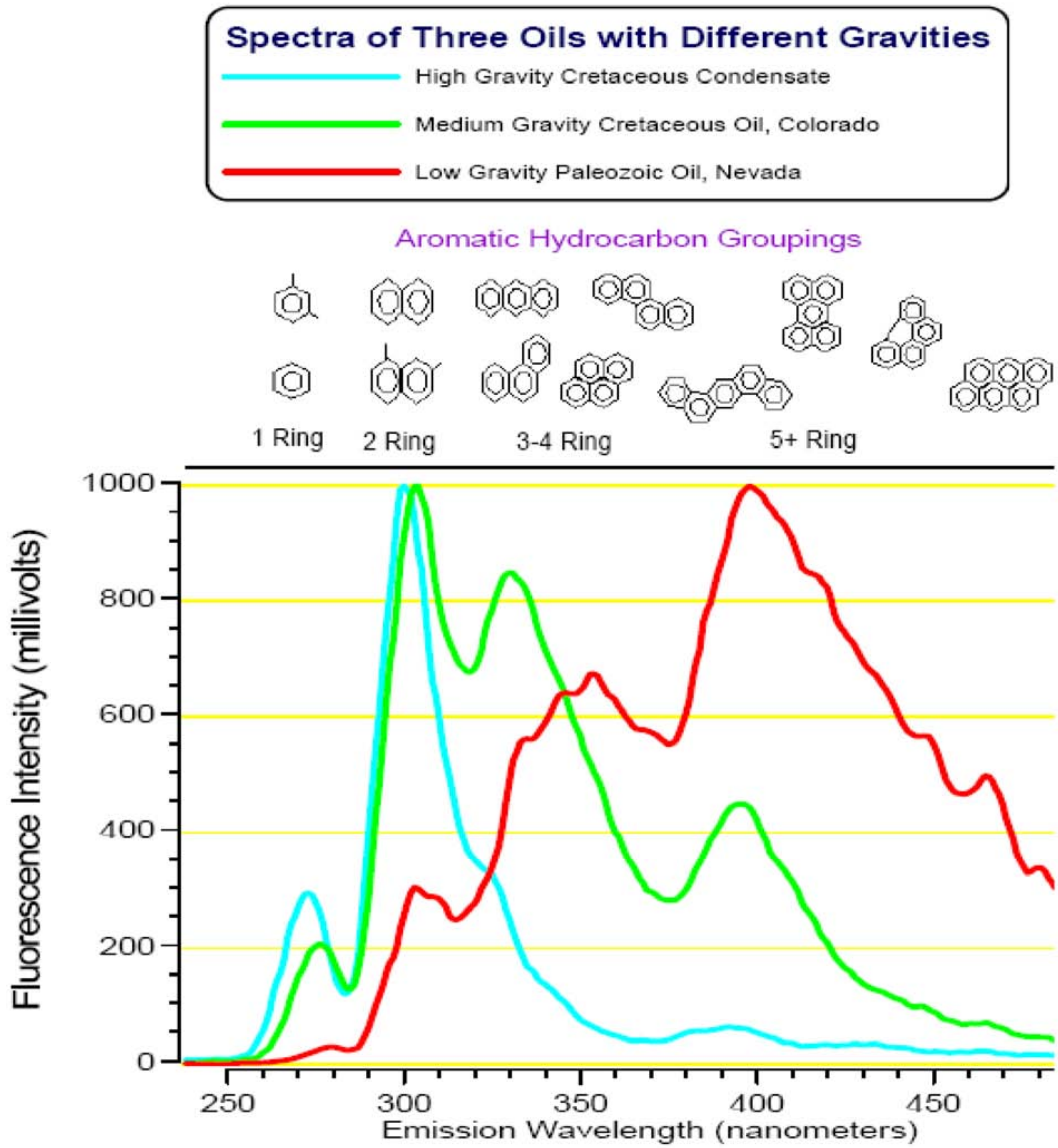


Figure 34. Synchronous scanned fluorescence spectra of high, medium, and low gravity oils.

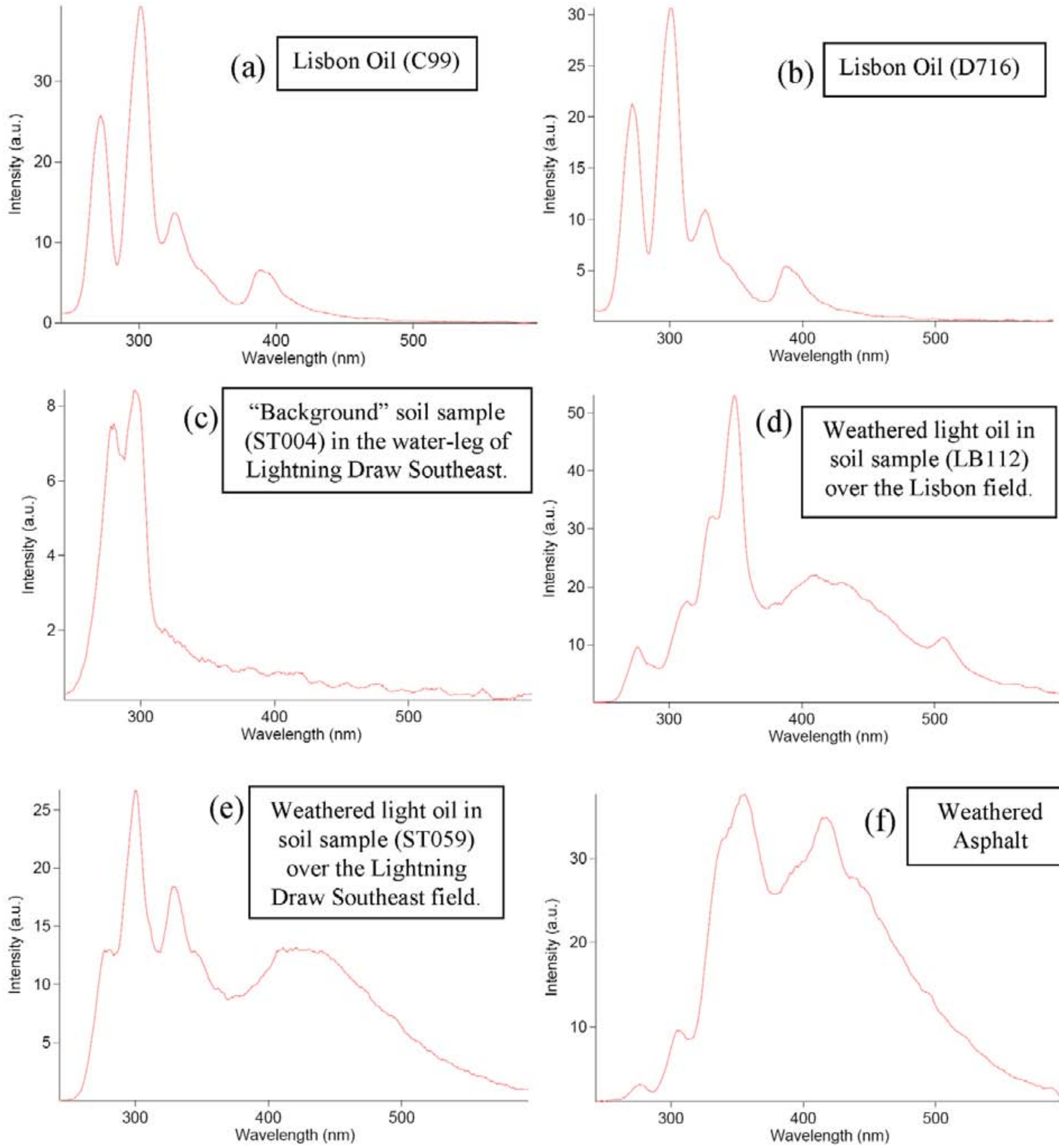


Figure 35. Synchronous scanned fluorescence spectra for Lisbon oil (a and b), background soil sample (c), weathered oil in soil over Lisbon field (d), weathered oil in soil over Lightning Draw Southeast field (e), and weathered asphalt (f).

data. The first factor reveals high loadings for the 395 nm, 431 nm, and 470 nm peaks (that is, heavy 4- to 6-ring aromatic residue in weathered light oil). Samples that are highly correlated with this factor are situated near crosscutting faults in the central, northwestern, and southeastern parts of the Lisbon field and over the southeastern half of the Lightning Draw Southeast field (figure 36). The second factor shows high loadings for the lighter 1- to 3-ring aromatic (less weathered?) peak intensities, which include the 277 nm, 305 nm, and 335 nm wavelengths (figure 37). Anomalous factor scores are confined mainly to the upper part of the Lisbon anticline and isolated anomalies are also evident along the Lightning Draw Southeast anticline (figure 37).

6-Foot-Deep Free-Gas Samples (Hydrocarbons and Fixed Gases)

Hydrocarbon concentration anomalies in free-gas samples show a marked spatial correlation with parts of the Lightning Draw Southeast field. For example, high-contrast propane anomalies are evident in three adjacent samples (over 600 feet [200 m]) northeast of the Federal No. 1-31 well (figure 38). Isohexane is also anomalous in two adjacent samples over 450 feet (150 m) from and in one sample immediately southwest of the Federal No. 1-31 well (figure 39). Hydrocarbon anomalies are not evident in the eight samples collected around the 2 White Rock Unit No. 1 well, off structure to the southeast (figure 7), where the Leadville Limestone was tight, or in the seven samples extracted around the dry No. 21-4 Federal well in the water leg of Lisbon field. Hydrogen is anomalous in three samples clustered around Federal No. 1-31 well and in one sample at the 2 White Rock Unit No. 1 well (figure 40). Carbon dioxide, which is a significant component of the produced gas (table 1), is anomalous in four free-as samples over Lightning Draw Southeast field (over and northeast of the Federal No. 1-31 well) and in two samples at the 2 White Rock Unit No. 1 well (figure 41).

Surface Soils (Major and Trace Elements)

Several trace metal anomalies are evident over both Lisbon and Lightning Draw Southeast fields (table 3). A larger number of trace metals are anomalous in surface soils over Lightning Draw Southeast compared with soils over Lisbon. One of the more interesting element assemblages, derived through factor analysis of the major/trace element data, is the association of cadmium, uranium, and molybdenum along with lower loadings for vanadium, manganese, and lead (figure 42). Samples that exhibit this assemblage occur as a northeast-trending anomaly in the central part of Lisbon field, and also as a 2400-foot-long (800-m) anomaly over the southeastern half of the Lightning Draw Southeast field. Isolated anomalies are also apparent elsewhere over the northwest-trending Lightning Draw Southeast anticline. The multi-sample anomaly at Lisbon is situated in a canyon with exposed and mineralized Triassic Chinle Formation, whereas the anomaly at Lightning Draw Southeast is contained mainly in stream alluvium.

Outcrop Fracture-Fill Lichen and Soils (Major and Trace Elements)

Outcrop lichen samples over Lisbon and Lightning Draw Southeast fields are anomalous in more trace metals than outcrop soils from the same fields (table 3). There are, however, anion anomalies in outcrop soils over Lisbon that are not apparent in the outcrop lichen

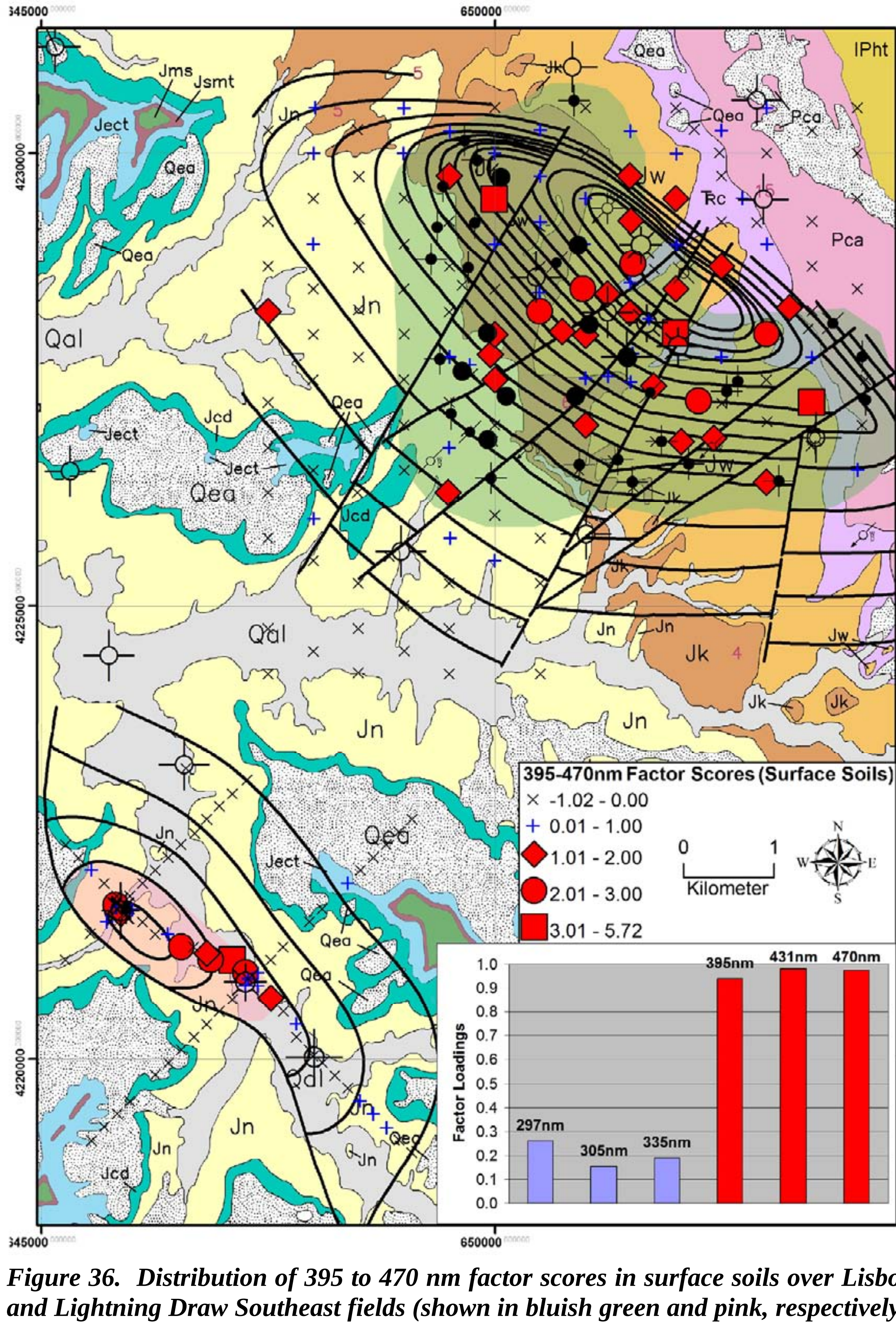


Figure 36. Distribution of 395 to 470 nm factor scores in surface soils over Lisbon and Lightning Draw Southeast fields (shown in bluish green and pink, respectively). Surface geology modified from Doelling (2005); see figures 8 and 10 for explanations of well symbols and geologic units. Form line contours based on top of structure of the Leadville Limestone shown on figures 8 and 9.

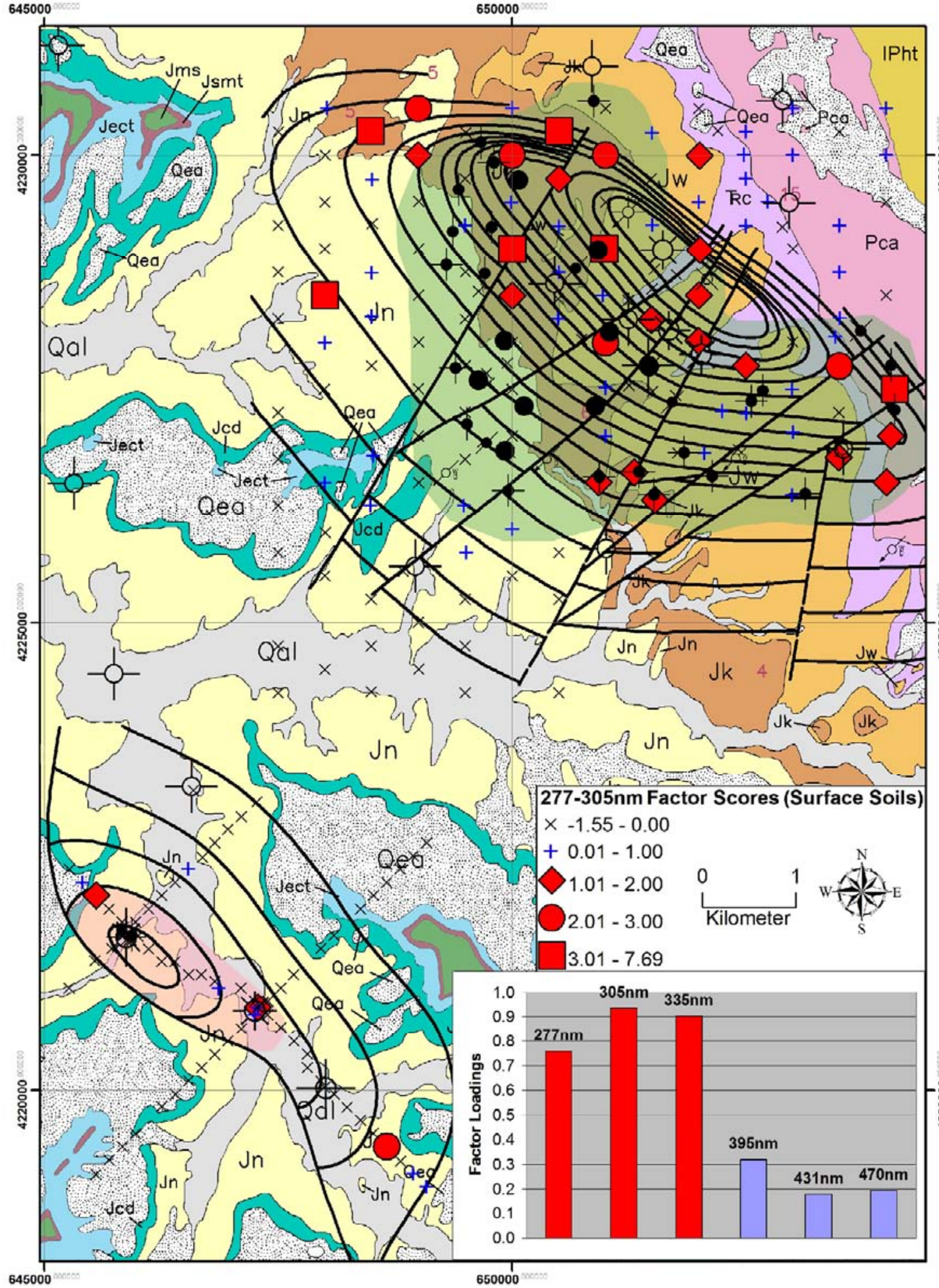


Figure 37. Distribution of 277 to 335 nm factor scores in surface soils over Lisbon and Lightning Draw Southeast fields. Surface geology modified from Doelling (2005); see figures 8 and 10 for explanations of well symbols and geologic units. Form line contours based on top of structure of the Leadville Limestone shown on figures 8 and 9.

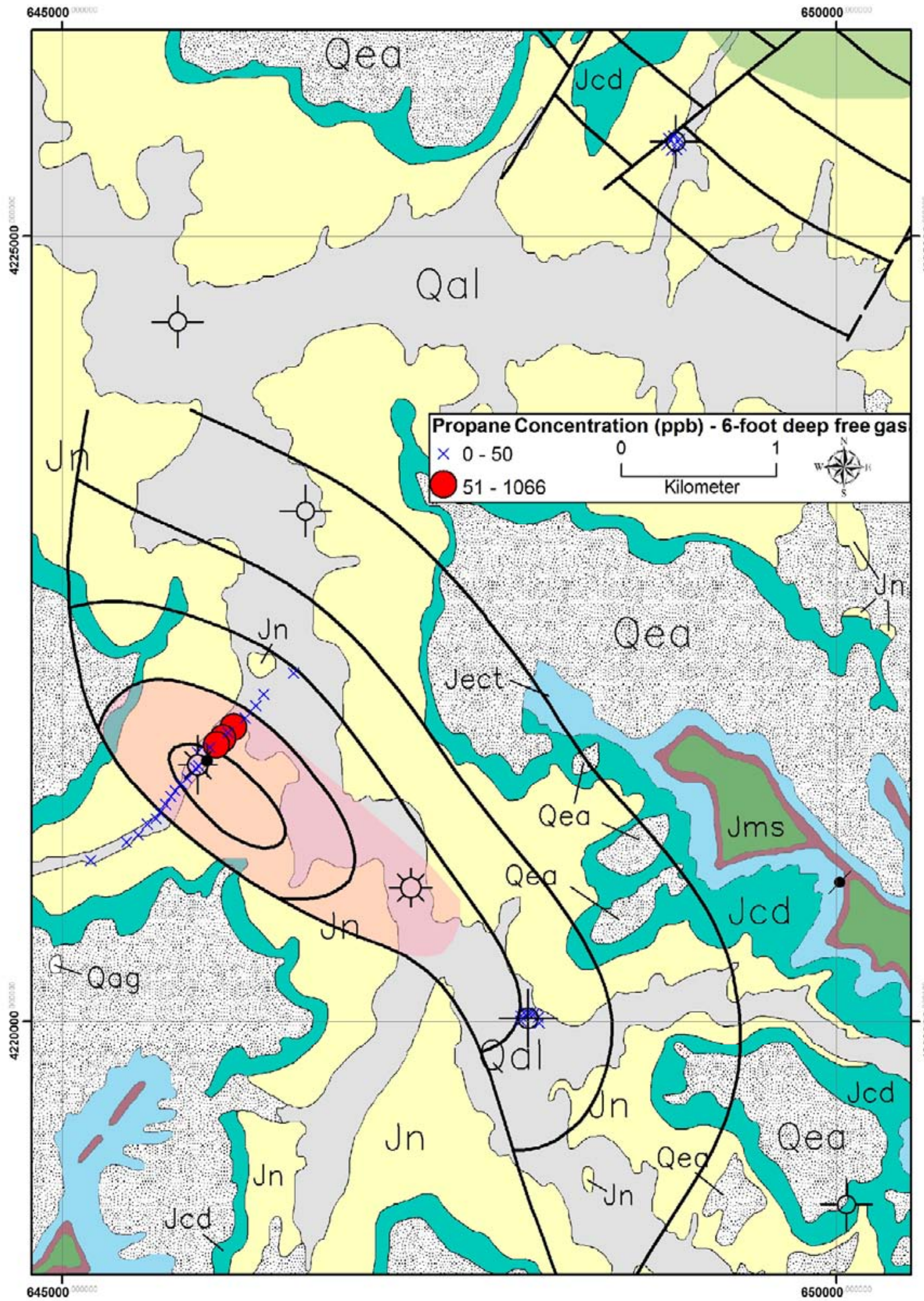


Figure 38. Distribution of propane concentrations in 6-foot-deep free gas over Lightning Draw Southeast field (shown in pink) and background areas. Surface geology modified from Doelling (2005); see figures 8 and 10 for explanations of well symbols and geologic units. Form line contours based on top of structure of the Leadville Limestone shown on figure 9.

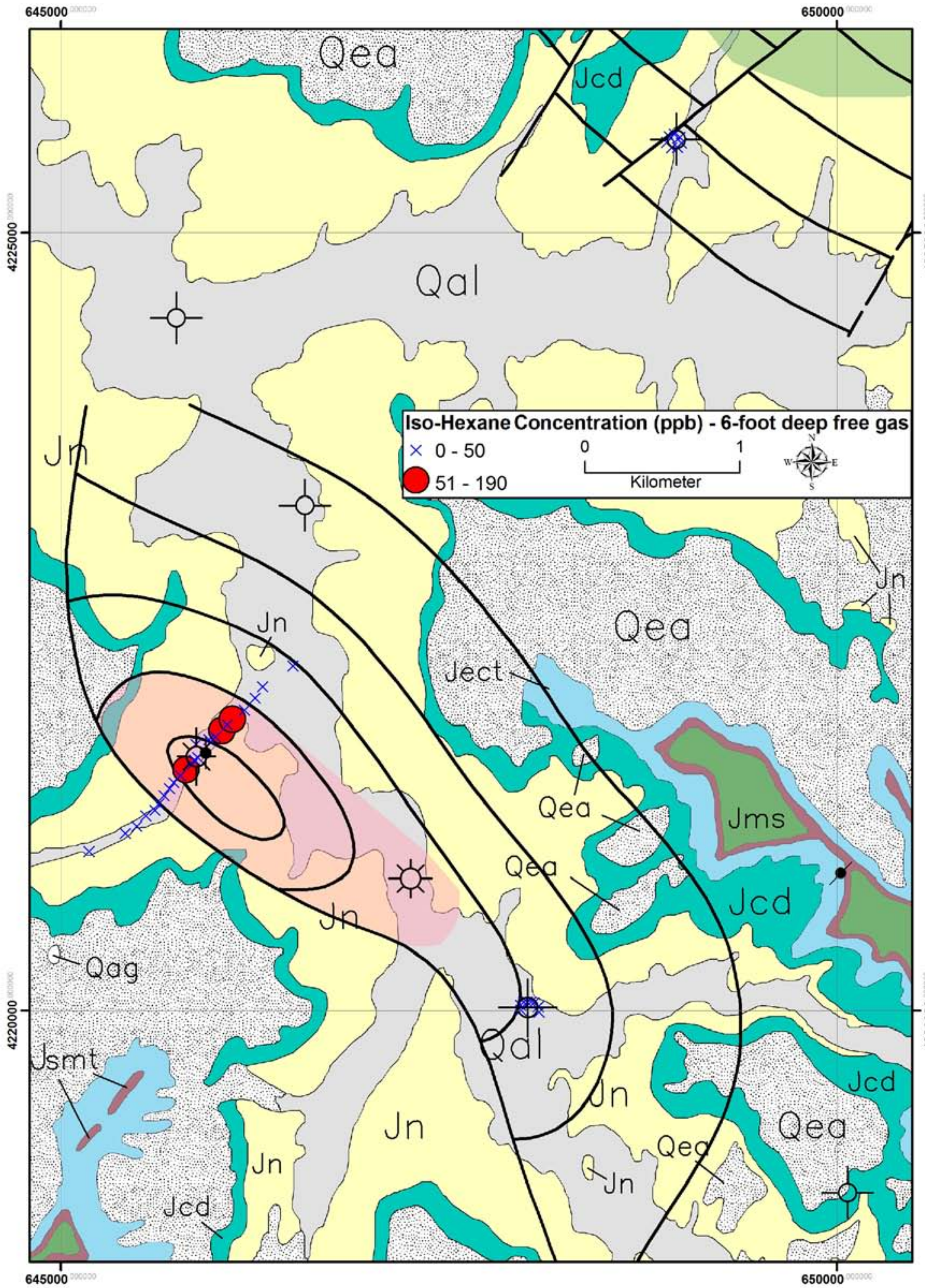


Figure 39. Distribution of isohexane concentrations in 6-foot-deep free gas over Lightning Draw Southeast field (shown in pink) and background areas. Surface geology modified from Doelling (2005); see figures 8 and 10 for explanations of well symbols and geologic units. Form line contours based on top of structure of the Leadville Limestone shown on figure 9.

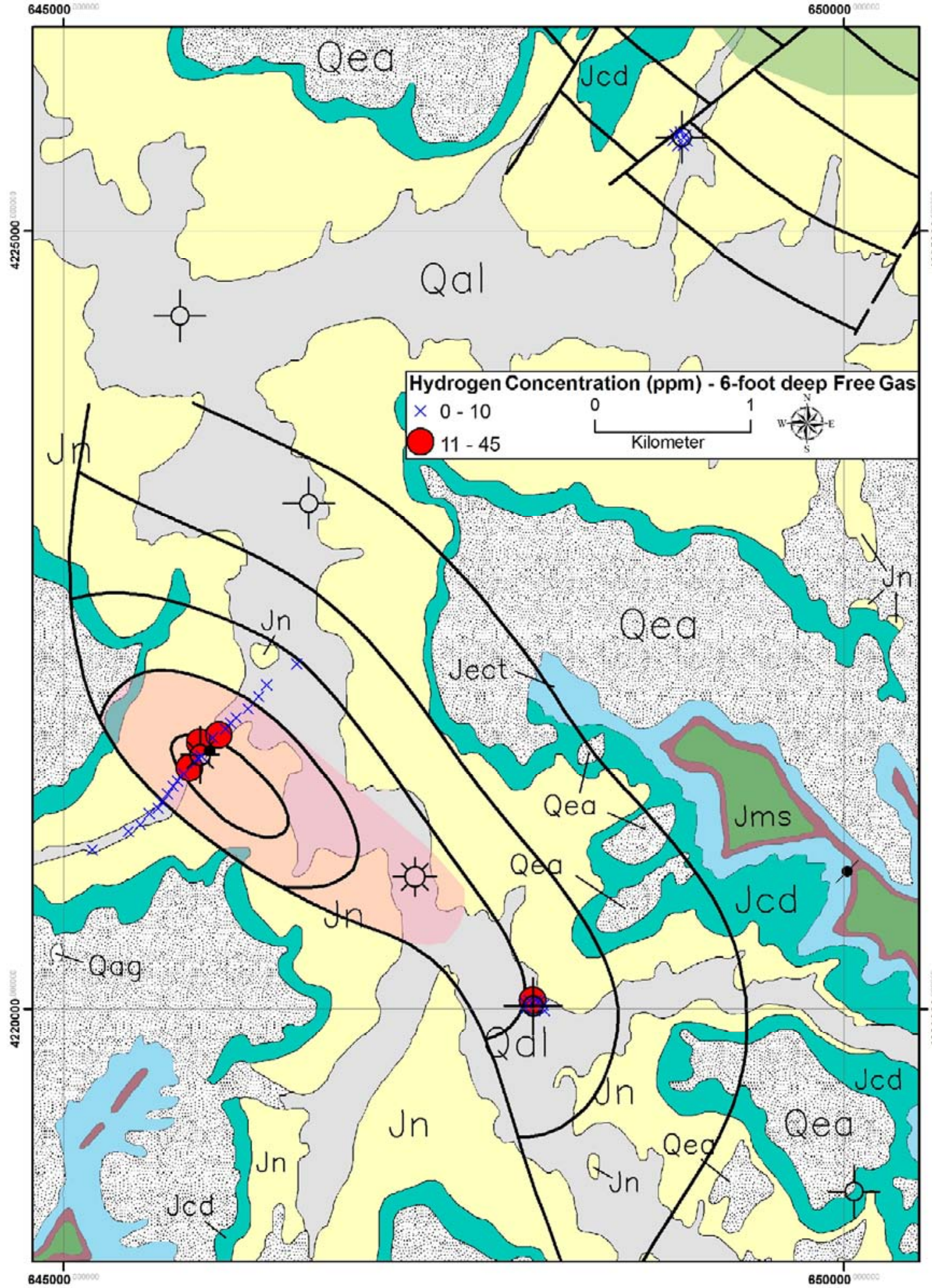


Figure 40. Distribution of hydrogen concentrations in 6-foot-deep free gas over Lightning Draw Southeast field (shown in pink) and background areas. Surface geology modified from Doelling (2005); see figures 8 and 10 for explanations of well symbols and geologic units. Form line contours based on top of structure of the Leadville Limestone shown on figure 9.

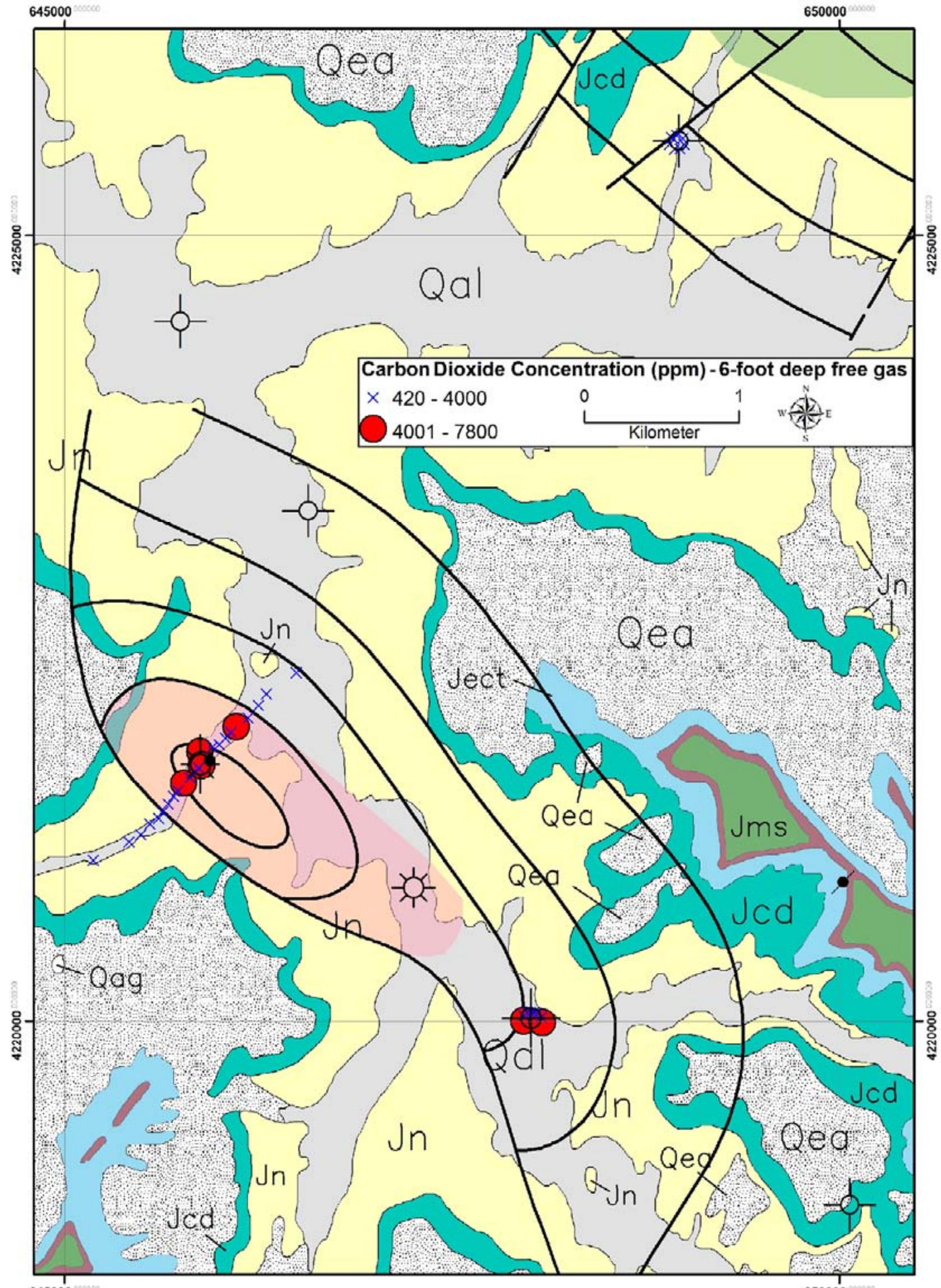


Figure 41. Distribution of carbon dioxide concentrations in 6-foot-deep free gas over Lightning Draw Southeast field (shown in pink) and background areas. Surface geology modified from Doelling (2005); see figures 8 and 10 for explanations of well symbols and geologic units. Form line contours based on top of structure of the Leadville Limestone shown on figure 9.

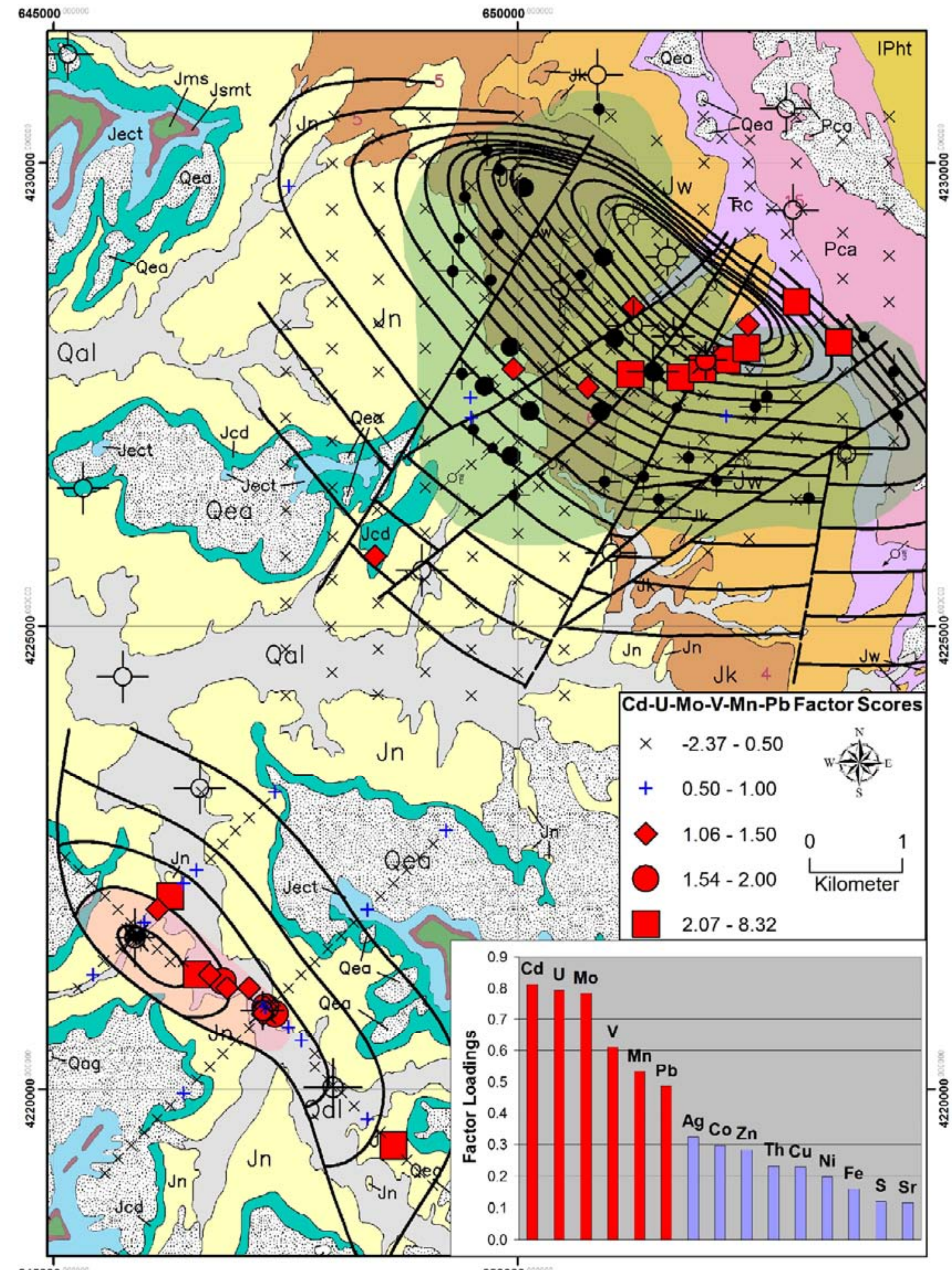


Figure 42. Distribution of cadmium-uranium-molybdenum-vanadium-manganese-lead factor scores in surface soils over Lisbon and Lightning Draw Southeast fields (shown in bluish green and pink, respectively). Surface geology modified from Doelling (2005); see figures 8 and 10 for explanations of well symbols and geologic units. Form line contours based on top of structure of the Leadville Limestone shown on figures 8 and 9.

samples. Uranium is anomalous in both outcrop lichen and soils over the gas cap of Lisbon in proximity to exposed mineralized Chinle Formation, but anomalies are not evident in these sample media over the Lisbon oil and water legs, nor over Lightning Draw Southeast field (figures 43 and 44).

Discussion

The study's main objective was to determine if a variety of low-cost, surface geochemical methods are useful as a complementary tool for Leadville Limestone exploration. The data presented above show that all of the methods tested identify significant anomalies that are spatially correlated with the productive areas of Lisbon and Lightning Draw Southeast fields. Raw hydrocarbon concentrations, expressed as Z-scores, reveal anomalies that are spatially associated with crosscutting faults on the productive part of the Lisbon anticline. These anomalies probably represent the surface expression of microseepage that ascended along these structures. It is doubtful that the anomalies are an artifact of surface contamination because:

(1) While some anomalies occur near current oil production, there are several productive wells without surface hydrocarbon anomalies.

(2) There are strong anomalies in areas with no current or historic production and upwind to producing areas.

(3) The anomalous hydrocarbons have different spatial distributions; benzene is mainly over the upper part of the structure whereas alkanes and other aromatics are clustered near crosscutting faults.

Discriminant analysis is a useful tool for distinguishing the microseepage over the productive parts of Lisbon and Lightning Draw Southeast fields from that of the non-productive Lisbon water leg. Microseepage in surface soils over the Lisbon gas cap is clearly distinguished from that over the water leg, and the most important variables for discrimination are alkanes and aromatics in the C_3 to C_6 range, which is not surprising considering the composition of produced gas from the field. This particular discriminant model predicts two samples as being gas prone over Lighting Draw Southeast field. Rather than only using samples collected at well sites as training sets, a better approach might be to use an array of samples over a much larger productive area to compare with the water leg. When such a model was tested here, more samples over Lightning Draw Southeast field are classified into the "productive" category. When analyses of surface soils around productive wells in Lightning Draw Southeast field are compared with the sample character from the Lisbon field, several samples exhibit the Lisbon gas-prone signature. In essence, the Lisbon discriminant model predicts production at Lightning Draw Southeast, and conversely the model at Lighting Draw Southeast predicts production at Lisbon. In both models, ethane and normal-butane are most influential in the distinction between "gas and water legs," which corresponds with the produced gas composition.

The outcrop fracture-fill lichen and soils seem to be a better sample media for discriminating between the compositional character of microseepage over the Lisbon gas cap,

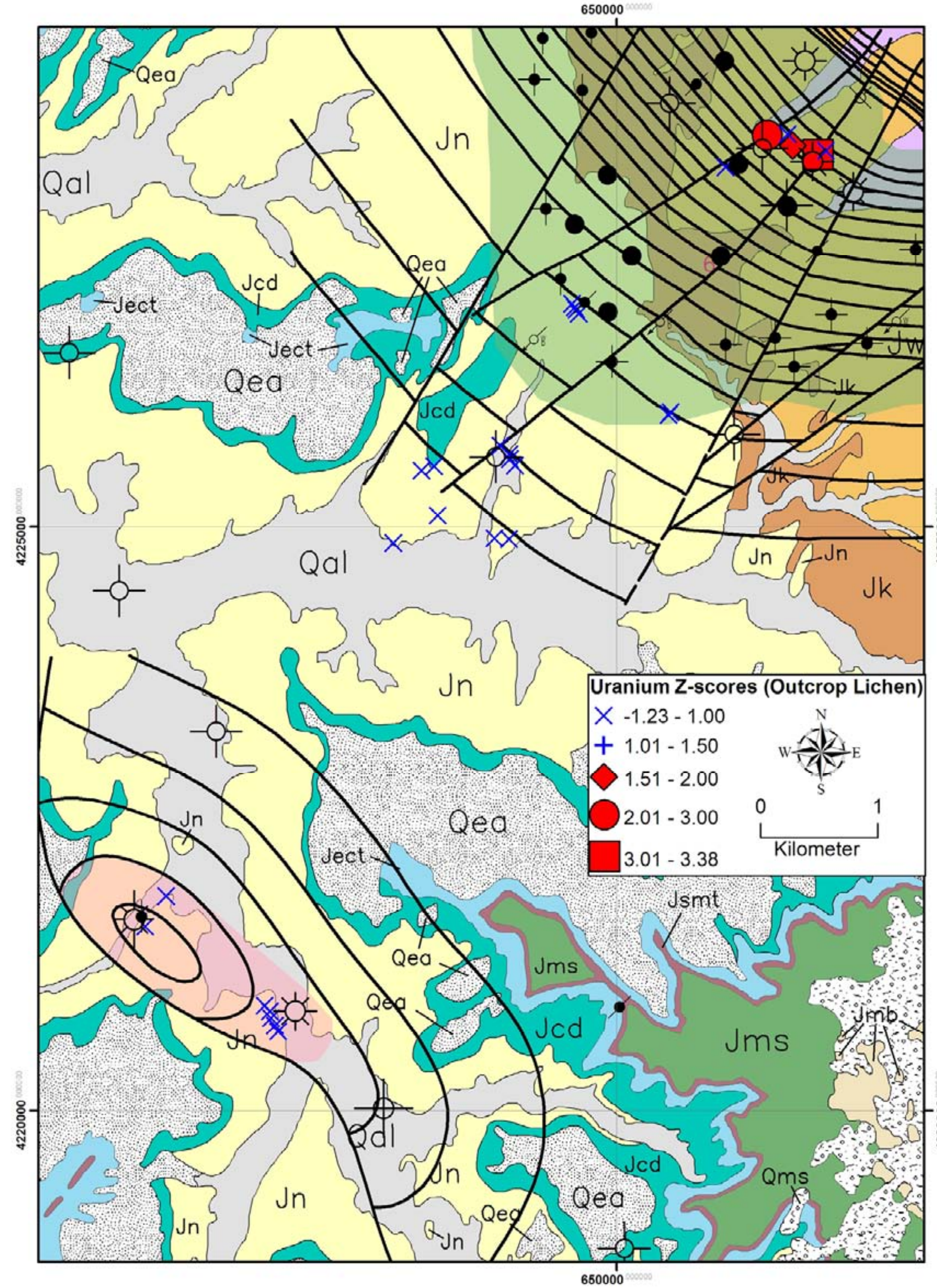


Figure 43. Distribution of uranium Z-scores in outcrop lichen over Lisbon and Lightning Draw Southeast fields (shown in bluish green and pink, respectively). Surface geology modified from Doelling (2005); see figures 8 and 10 for explanations of well symbols and geologic units. Form line contours based on top of structure of the Leadville Limestone shown on figures 8 and 9.

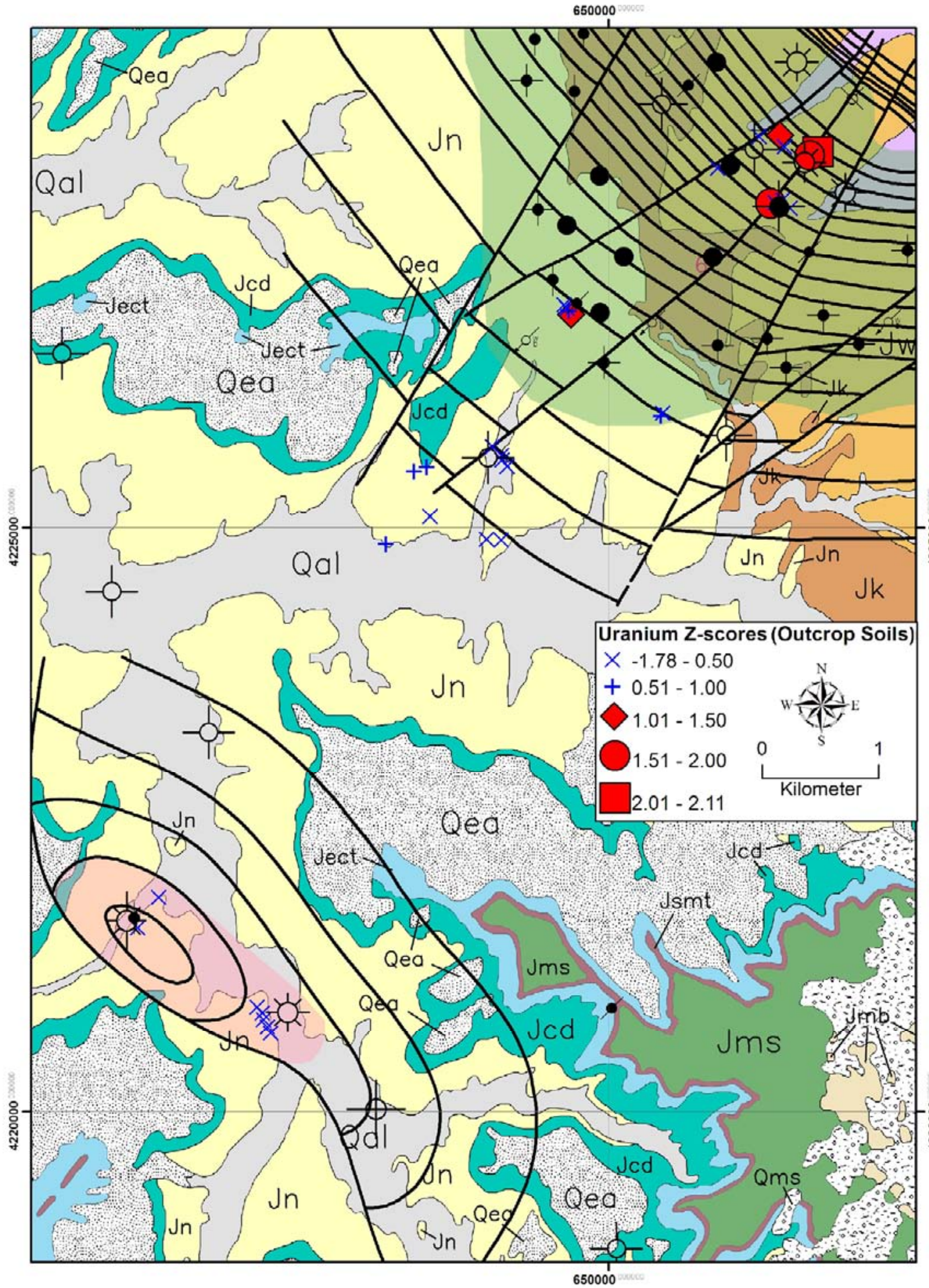


Figure 44. Distribution of uranium Z-scores in outcrop soils over Lisbon and Lightning Draw Southeast fields (shown in bluish green and pink, respectively). Surface geology modified from Doelling (2005); see figures 8 and 10 for explanations of well symbols and geologic units. Form line contours based on top of structure of the Leadville Limestone shown on figures 8 and 9.

oil leg, and water leg. The outcrop soils over Lightning Draw Southeast field best match the Lisbon gas cap samples as a training set. On the other hand, the Lisbon outcrop lichen samples best match the productive Lightning Draw Southeast samples as a training set. In both outcrop lichen and soil samples, the most important variable indicating gas is methane while for oil it is propane. The reasons the outcrop fracture-fill media are better "dicriminators" are unknown, but the fact that most microseepage would likely migrate up through joints in outcrops could contribute to better their discriminating potential.

There are heavy aromatic hydrocarbon anomalies (that is, 395 to 470 nm factor scores) in surface soils that are spatially correlated with crosscutting faults on the Lisbon structure and the southeastern half of the Lightning Draw Southeast field. The fluorescence spectral pattern of these anomalies suggests the presence of weathered light oil in the samples. The lighter aromatics (that is, 277 to 335 nm factor scores) are anomalous mainly over the upper part of the Lisbon structure and sporadically along the Lightning Draw Southeast structure. It is doubtful that the origin of these anomalies solely represents anthropogenic contamination from active or shut-in wells and paved roads because:

(1) While some anomalies occur near current oil production, there are several productive wells without fluorescence anomalies.

(2) There are strong anomalies in areas with no current or historic production and upwind to producing areas.

(3) Soils collected near paved roads were removed from the database to eliminate false anomalies related to entrained asphalt dust.

(4) There are no paved roads in the vicinity of the 2400-foot-long (800-m), multi-sample anomaly over the southeastern half of Lightning Draw, and the anomaly is upwind of the Evelyn Chambers Government No. 1 well.

These multi-sample, heavy aromatic (weathered light oil) anomalies, therefore, probably represent seeps of condensate along structures the crosscut the Lisbon anticline and those that parallel the Lightning Draw Southeast anticline.

More direct evidence of current-day hydrocarbon seepage is provided by the ethane through hexane anomalies in free gas samples over the Lightning Draw Southeast field. Carbon dioxide, which is also a significant component of the produced gas from the Leadville, is also anomalous over the field and off structure to the southeast.

The strong cadmium-uranium-molybdenum elemental association (with lower loadings for vanadium, manganese, and lead) mapped at Lisbon and Lighting Draw Southeast fields may have separate origins and emplacement mechanisms. Anomalies in the canyon with exposed Chinle Formation almost certainly are genetically tied to this formation through mechanical and/or chemical dispersion processes. Uranium concentrations up to 45 parts per million (ppm) were noted in soils close to the uranium occurrences in the Chinle. The trace metal association is also anomalous in consecutive samples over the southeastern half of the Lightning Draw Southeast field and in isolated samples off structure. The metal anomalies over the field are spatially correlated with the heavy aromatic hydrocarbon anomalies. Because there is no Chinle or other uranium-bearing formations exposed at Lightning Draw Southeast, the anomalies may owe their origin to chemical dispersion of these elements by an oxidized fluid that ascended a fault and precipitated these trace metals in the reduced part of the fault where heavy hydrocarbons are present. Alternatively, the trace metals may have precipitated in a hydrocarbon reservoir below, and then were brought up to surface with the hydrocarbon seeps documented here. The outcrop lichen samples show a larger number of high-contrast trace metal anomalies in comparison with the outcrop soils. This could reflect the ability of the lichen to hold (chelate) metals obtained by uptake from ground water.

TECHNOLOGY TRANSFER

The UGS is the Principal Investigator and prime contractor for the Leadville Limestone project, described in this report. All maps, cross sections, lab analyses, reports, databases, and other deliverables produced for the project will be published in interactive, menu-driven digital (Web-based and compact disc) and hard-copy formats by the UGS for presentation to the petroleum industry. Syntheses and highlights will be submitted to refereed journals, as appropriate, such as the *American Association of Petroleum Geologists (AAPG) Bulletin* and *Journal of Petroleum Technology*, and to trade publications such as the *Oil and Gas Journal*. This information will also be released through the UGS periodical *Survey Notes* and be posted on the UGS Paradox Basin project Web page.

The technology-transfer plan includes the formation of a Technical Advisory Board and a Stake Holders Board. These boards meet annually with the project technical team members. The Technical Advisory Board advises the technical team on the direction of study, reviews technical progress, recommends changes and additions to the study, and provides data. The Technical Advisory Board is composed of Leadville field operators and those who are actively exploring for Leadville hydrocarbons in Utah and Colorado. This board ensures direct communication of the study methods and results to the operators. The Stake Holders Board is composed of groups that have a financial interest in the study area including representatives from the State of Utah (School and Institutional Trust Lands Administration, and Utah Division of Oil, Gas and Mining) and the federal government (Bureau of Land Management). The members of the Technical Advisory and Stake Holders Boards receive all semi-annual technical reports, copies of all publications, and other material resulting from the study. Board members also provide field and reservoir data.

An abstract describing the surface geochemical survey and results was submitted to the AAPG, for presentation at the October 2007 Rocky Mountain Section meeting at Snowbird, Utah. A poster titled “New Techniques for New Discoveries – Results from the Lisbon Field Area, Paradox Basin, Utah” was prepared by D.M. Seneshen, T.C. Chidsey, Jr., C.D. Morgan, and M.D. Vanden Berg for presentation at the 2007 AAPG annual convention in Long Beach, California.

Utah Geological Survey Survey Notes and Web Site

The UGS publication *Survey Notes* provides non-technical information on contemporary geologic topics, issues, events, and ongoing UGS projects to Utah's geologic community, educators, state and local officials and other decision-makers, and the public. *Survey Notes* is published three times yearly. Single copies are distributed free of charge and reproduction (with recognition of source) is encouraged. The UGS maintains a database that includes those companies or individuals specifically interested in the Leadville project or other DOE-sponsored UGS projects. They receive *Survey Notes* and notification of project publications and workshops.

The UGS maintains a Web site on the Internet, http://geology.utah.gov. The UGS site includes a page under the heading *Oil, Gas, Coal, & CO_2*, which describes the UGS/DOE cooperative studies past and present (PUMPII, Paradox Basin [two projects evaluating the Pennsylvanian Paradox Formation], Ferron Sandstone, Bluebell field, Green River Formation), and has a link to the DOE Web site. Each UGS/DOE cooperative study also has its own separate page on the UGS Web site. The Leadville Limestone project page, http://geology.utah.gov/emp/leadville/index.htm, contains (1) a project location map, (2) a description of the project, (3) a reference list of all publications that are a direct result of the project, (4) poster presentations, and (5) semi-annual technical progress reports.

Presentations

The following presentations were made during the reporting period as part of the technology transfer activities:

"Gas and Oil in Utah: Potential, New Discoveries, and Hot Plays" by T.C. Chidsey, November 9, 2006, presented at the fall Utah Alumni Meeting sponsored by BP America Producing Company and Brigham Young University, Houston, Texas. An overview of major Utah oil plays including the Mississippian Leadville Limestone play and the surface geochemical survey program were included in the presentation.

"Current Highlights and Major Oil and Gas Plays of Utah" by T.C. Chidsey, March 1, 2007, presented at the monthly meeting of the Utah Association of Professional Landmen, Salt Lake City, Utah. An overview of major Utah oil plays including the Mississippian Leadville Limestone play and the surface geochemical survey program were included in the presentation.

"The Surface Geochemical Expression of Carbonate-Hosted Hydrocarbon Reservoirs" by David Seneshen and Jim Viellenave, March 22, 2007, at the Petroleum Technology Transfer Council workshop "Michigan Field Experiences - Focus on Hydrothermal Dolomites," Mount Pleasant, Michigan. The presentation included an overview of the Leadville project and the surface geochemical survey.

Project Publication

Chidsey, T.C., Jr., Morgan, C.D., Vanden Berg, M.D., and Seneshen, D.M., 2006, The Mississippian Leadville Limestone exploration play, Utah and Colorado: exploration techniques and studies for independents – semi-annual technical progress report for the period April 1, 2006 to September 30, 2006: U.S. Department of Energy, DOE/BC15424-6, 39 p.

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

The Mississippian Leadville Limestone is a shallow, open-marine, carbonate-shelf deposit. The Leadville has produced over 53 million barrels (8.4 million m^3) of oil from seven fields in the Paradox fold and fault belt of the Paradox Basin, Utah and Colorado. Most Leadville oil and gas production is from basement-involved structural traps. All of these fields are currently operated by independent producers. This environmentally sensitive, 7500-square-mile (19,400 km^2) area is relatively unexplored. Only independent producers continue to hunt for Leadville oil targets in the region. Lisbon field accounts for most of the Leadville oil production in the Paradox Basin. Its reservoir characteristics, particularly diagenetic overprinting and history, and Leadville lithofacies can be applied regionally to other fields and exploration trends in the basin (including the recently discovered Lightning Draw Southeast field to the southwest). Therefore, Lisbon field was selected as the case-study field for the Leadville Limestone project.

Surface geochemical surveys have proved to help identify areas of poorly drained or by-passed oil in other basins. Lisbon field is ideal for a surface geochemical survey because proven hydrocarbons underlie the area, sample sites are relatively easily accessible, and the surface geology is similar to the structure of the field. Lisbon field is the largest Leadville producer and is still actively producing oil and gas. The surface geology at Lisbon field consists of a major anticline along a large normal fault. Proving the success of relatively low-cost geochemical surveys at Lisbon field allows independent operators to reduce risks and minimize impacts on environmentally sensitive areas while exploring for Leadville targets.

The geochemical survey consisted of collecting about 200 shallow soil samples at 1500-foot intervals (500 m) on a 16-square-mile (42 km^2) rectangular grid over and around the Lisbon field to map the spatial distribution of surface hydrocarbon anomalies. The sampling grid extends beyond the proven limits of Lisbon field to establish background readings. The area chosen sufficiently covers the oil leg, gas cap, and water leg/background barren areas. In addition, 90 samples were collected over gas, oil, and dry wells for analogue matching purposes and to refine the discriminant model for Lisbon field. To the southwest, the recently discovered Lightning Draw Southeast field has similar geology to Lisbon field, both in terms of structure and a Leadville reservoir. It consists of two producing wells, primarily gas and condensate, along with barren dry wells off structure. However, the field is still near original reservoir pressure and therefore hydrocarbon microseepage to the surface may be more significant than at Lisbon field. The surface geochemical survey was expanded to include this new field and the surrounding area with about 80 samples collected along northwest-southeast and northeast-southwest grid lines and 45 samples around both the producing wells and barren dry wells. Free-gas samples (40) were collected over Lightning Draw Southeast field and known non-productive areas off the structure. Finally, joints in the Jurassic Navajo and Entrada Sandstones were also sampled as pathways for hydrocarbon microseepage to the surface. Sandstone outcrops have parallel and polygonal joints filled with soil, sand, bryophytes, and lichen. Over 60 samples were collected along joints for geochemical analyses.

The soil samples were placed and stored in airtight, Teflon-sealed glass soil jars to prevent hydrocarbon contamination during transport. Samples were dried and sieved, and aliquots weighed out for geochemical analyses for 40 hydrocarbon compounds in the C_1 to C_{12} range, 53 major and trace elements, seven anion species, and for synchronous scanned fluorescence analyses.

The main conclusion drawn from this evaluation of surface geochemical methods over the Lisbon and Lightning Draw Southeast fields is that certain low cost ($100 to $200 per sample), non-invasive geochemical methods are effective as pre-screening and follow-up tools in the exploration for Leadville hydrocarbon reservoirs. More specifically, the conclusions are as follows:

(1) Hydrocarbon microseepage over the gas cap, oil leg, and water leg at Lisbon field is distinguished based on a linear combination of thermally desorbed hydrocarbons in surface soil samples, and outcrop fracture-fill soil and lichen samples. Important variables for distinguishing productive and barren areas are alkanes and aromatics in the C_1 to C_6 range. The compositional character of microseepage in surface soils is more distinct over the Lisbon gas cap relative to the water leg than is the oil leg. Both the outcrop lichen and soil samples better discriminate between the Lisbon gas cap, oil leg, and water leg in comparison with the surface soils. Outcrop fracture-fill media would therefore be the preferred sample media in areas of abundant outcrop. Productive "Lisbon-type" microseepage signatures are observed over Lightning Draw Southeast field southwest of Lisbon field. Conversely, compositional signatures over Lightning Draw Southeast field also predict productive parts of Lisbon.

(2) Hydrocarbon concentrations in the C_1 to C_{12} range are also anomalous over parts of Lisbon and Lightning Draw Southeast fields. The anomalies probably represent microseepage that ascended faults in the Lisbon and Lightning Draw Southeast anticlines because of the close spatial association of the anomalies with documented faults, particularly in the case of Lisbon. It is unlikely that the hydrocarbon anomalies reflect surface contamination from production because most anomalies occur upwind of production, and some anomalies are situated in areas with no current or historic production.

(3) Both light and heavy aromatic hydrocarbon anomalies are evident in surface soils over Lisbon and Lightning Draw Southeast fields. Fluorescence spectral patterns in anomalous areas are indicative of a weathered light oil or condensate. The dust from asphalt roads contained in soil samples is a potential contaminant that creates false anomalies in the heavy aromatic spectrum (that is, 395 to 470 nm SSF intensities). Contaminated samples near roads were therefore removed from the database prior to interpretation. Heavy aromatic hydrocarbon anomalies are spatially correlated with crosscutting faults at Lisbon and a 2400-foot-long (800 m) anomaly occurs upwind of an active gas condensate well without nearby paved roads. The anomalies therefore likely reflect condensate seeps along faults in the Lisbon and Lightning Draw Southeast anticlines.

(4) Narrow (that is, 450 to 900 feet [150-300 m]) normal- and iso-alkane anomalies in the C_2 to C_6 range are evident in 6-foot-deep (2 m) free-gas samples over Lightning Draw Southeast field. Carbon dioxide and hydrogen are also anomalous in free gas along the trend of the field.

(5) An anomalous cadmium-uranium-molybdenum-vanadium-manganese-lead assemblage

in surface soils is spatially associated with productive parts of Lisbon and Lightning Draw Southeast fields. In the case of Lisbon field this element assemblage presumably reflects mechanical and chemical dispersion from the exposed Chinle Formation. At Lightning Draw Southeast field, however, there is no exposed Chinle, and thus the anomalies probably reflect chemical dispersion of these elements from an underlying source. In both cases, heavy hydrocarbons are present in the surface media to act as a reductant for deposition of these elements. A larger number of major/trace elements are anomalous over productive areas in outcrop lichen versus outcrop fracture soils, possibly reflecting the ability of the lichen to hold (chelate) metals obtained by uptake from ground water. The lichen would therefore be a better sample medium in areas of abundant outcrop in terms of high-contrast, trace-metal anomalies.

Recommendations for future surface geochemical surveys for Leadville Limestone exploration in the Paradox Basin are:

(1) Reconnaissance exploration should include the collection of surface soils (outcrop fracture-fill lichen and soils where applicable) for hydrocarbon and major/trace element analyses.

(2) Anomalous areas identified in reconnaissance soil surveys should be followed up with the extraction and hydrocarbon analysis of deep free-gas samples collected at short horizontal intervals (<300 feet [<100 m]). The short-interval free-gas method is also recommended for testing existing seismic anomalies for hydrocarbon and carbon dioxide anomalies.

ACKNOWLEDGMENTS

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